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BOXWORK SIDERITE.

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THE occurrence, in the mines of the Phelps Dodge Corporation at Bisbee, Arizona, of an apparently unusual type of iron carbonate, has prompted the writers to offer a shore description of it. This siderite, from its structure and appearance, has been given the name of "siderite boxwork."[1] It occurs as a vesicular rock, running as high as forty per cent. voids, in which the cavities are roughly angular or box-like in shape, separated by plates or sheets of siderite. The cavities range from minute pores, some of them probably due to shrinkage, to holes several inches in their larger dimension, and the plates vary from a tenth of an inch to an inch in thickness. There is a marked tendency for a majority of the plates to lie parallel, being intersected at irregular intervals by other plates which cut them at all angles. The known bodies of boxwork siderite are quite extensive. One incompletely delimited area, under a large chalcocite ore body, has an area on one level of at least twenty thousand square feet, and a thickness in places of at least fifty feet. The temperature in this area is markedly above the average mine temperature, indicating that reactions connected with the formation of the siderite are still in progress there. At its edges, the siderite may end rather sharply against massive

[1] The occurrence was mentioned and named by Bonillas, Y. S., Tenny, J. B., and Fuechere, L., *Trans. A. I. M. E.*, vol. 55, pp. 284–355; and by Augustus Locke in "Leached Outcrops as Guides to Copper Ore," Williams and Wilkins, 1926.

pyrite, porphyry, or even fresh limestone, or may merge indistinctly into fresh or altered limestone.

Although siderite is the predominating mineral in the typical boxwork, smithsonite is also found in much the same form, in places closely intermingled with the siderite.[2] The siderite plates may have cores of the sulphides of iron, copper, lead or zinc, and among other associated minerals are found calcite, silica, kaolin, chalcocite, and rarely gypsum. The cavities are commonly filled with carbon dioxide, which drains off when they are cut by mining operations. Many variations of the typical boxwork structure are encountered; the cavities may be suppressed or almost absent. The color of the formation ranges from gray-white to brownish yellow.

In the majority of cases, siderite boxwork masses have been found to underlie copper ore bodies in their earlier stages of oxidation. Since almost all of the hypogene copper ores of Bisbee contain considerably more iron than copper, and since the ratio of copper to iron increases markedly as the bodies become enriched by secondary chalcocite through replacement of pyrite, the natural deduction is that the siderite is formed by interaction of solutions of iron sulphate derived from the ore bodies with unaltered limestone adjacent to the ore. The chemistry of this process will be discussed in greater detail in the latter part of this paper.

Since the boxwork siderite is frequently found underneath oxidizing ore bodies, its use as a guide to ore is immediately suggested. And as such it has, in Bisbee at least, a real value. This value is somewhat mitigated by two facts. First, there is no real reason why bodies of pure pyrite cannot form boxwork siderite as well as bodies of cupriferous sulphides. Although no difference has as yet been noted between boxwork siderite formed from cupriferous and non-cupriferous sulphide bodies, it has been suggested that the relative amounts of the metals accompanying the

[2] The authors have not made a microscopic study of the relations of the minerals accompanying the siderite.

siderite may furnish some clue as to this. A typical analysis of the siderite under an enriched cupriferous ore body is as follows:

Au_{oz}	Ag_{oz}	Cu	Pb	Zn	Fe	S	CaO	MgO	Mn	SiO_2
.01	.33	.35	Nil	5.6	29.5	0.5	3.5	3.4	5.7	3.6

Second, the supergene solutions that produce the siderite do not of necessity travel vertically downward, but are frequently carried laterally by bedding planes or fractures in the limestones. The

FIG. 1 (left). Boxwork Siderite.

FIG. 2 (right). Boxwork Siderite altered to Boxwork Limonite.

possibility is also suggested that where ore is underlain by rock other than calcium carbonate, the solutions may travel through or around it, possibly for considerable distances, before finding conditions suitable for deposition. An occurrence recently disclosed, where a small chalcocite ore body is underlain by a sill of porphyry, which is in turn underlain by boxwork siderite, suggests that this process may take place on a larger scale than has hitherto been observed.

In the Bisbee district, ore is known at all depths below the surface to a present maximum of some 2500 feet. Consequently ore bodies occur in all stages of oxidation. Those to which oxidizing ground waters have not as yet penetrated are unaccompanied by siderite. Those whose upper parts are more or less completely oxidized, and whose lower parts are in the stage of deposition of

secondary chalcocite, exhibit the siderite below them in its most typical form. But those ore bodies in which oxidation has proceeded to or near its final stages also show results of the same process. In this latter case, the siderite has oxidized to the hydrated oxides of iron, frequently with little change in its original structure. These oxides, however, are usually weaker structurally than the pre-existing siderite, and have, therefore, been crushed and compressed by the weight of overlying rocks, causing collapsing and slumping of the overlying ground, which probably accompanies and augments the "oxidation slumping" described by Wisser.[3] After this stage has been reached, the oxidation and migration of the copper in the ore body commonly progresses so far that it is redeposited as oxides or carbonates in the limonitic boxwork which represents the oxidized siderite. Calcite crystals may also form in the vugs of the boxwork. In rare instances, it may be that the copper even passes through the boxwork and deposits below it, so that in its very latest stages, the boxwork debris may actually become a guide pointing downward rather than upward to ore.

Occasionally this slumping has been observed to take place even before the siderite has oxidized to the limonitic minerals. Here it has been caused by weakening of the ground by the formation of the numerous cavities of the siderite. In its collapse, the siderite will bring down, as a jumbled breccia, the overlying formations, which may be either more siderite or even the lower parts of the ore body itself. The solutions furnishing the iron, however, may not have been exhausted before the collapse of the siderite, and the breccia formed by that collapse may be recemented by a "second generation" of siderite.

There is suggested the question "is the siderite formed by metasomatic replacement of the limestone, or does it deposit from solution in pre-existing cavities?" The answer appears to be "both." The typical siderite plates, by their shape and relation to each other, clearly suggest that their position was controlled by the bedding planes of the limestone and by small fractures

[3] Wisser, E. W., "Econ. Geol.," vol. 22, No. 8, Dec., 1927.

cutting those planes. This implies that the solutions entered the limestone by those channels, and began to replace it metasomatically with siderite. But the cavities are almost invariably lined with rounded, botryoidal or euhedral coatings of siderite, or with minute crystals of it arranged in rosette groups, suggesting in this case deposition from solution on the walls of an open space. Further, the "second generation" of siderite above referred to is found cementing breccia fragments, such as siderite or copper-iron sulphides, which could not have supplied the carbon dioxide necessary to the reaction which produced the siderite. Here the siderite was probably deposited from solution by dessication or other alteration of the solution, rather then by metasomatic replacement of a pre-existing rock.

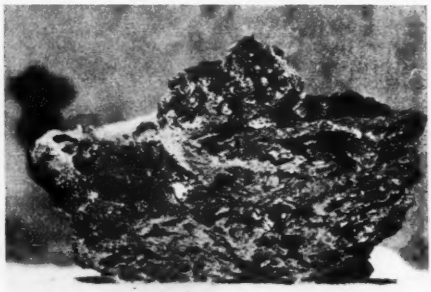

FIG. 3. Carbonates of Copper in Boxwork Form.

Iron is not the only metal whose sulphate reacts with calcium carbonate to form a metallic carbonate with this sort of structure. Malachite and azurite of similar shape are encountered at Bisbee (Fig. 3), smithsonite of similar appearance and occurrence has been described by Loughlin [4] and Knopf,[5] and smithsonite, as has

[4] G. F. Loughlin, "Oxidized Zinc Ores at Leadville, Colorado," U. S. Geol. Surv. Bull. 681, 1918.

"The Oxidized Zinc Ores of the Tintic District, Utah," ECON. GEOL., vol. 9, No. 1, pp. 1–19, 1914.

[5] Adolph Knopf, "Mineral Resources of the Inyo and White Mts., California," U. S. Geol. Surv. Bull 540-B, 1913.

been mentioned, is frequently associated with siderite in the typical boxwork areas at Bisbee. Nor is Bisbee the only locality exhibiting this phenomenon. The writers have observed siderite boxwork at the Altar and Cananea prospect in northern Sonora, at a lead prospect near Paradise, Arizona, and the limonitic oxidation product of siderite boxwork in the Lone Mountain Mine near Hiltano, Arizona, and a prospect near Winkleman, Arizona. Smithsonite of much the same structure was observed in the San Juan mine, near Tombstone, Arizona. In all these cases except the last, the metallic carbonate has been definitely determined to be below (or beside) bodies of oxidizing copper, lead, or zinz ore. Probably the occurrence of this form of siderite is known elsewhere, or has escaped notice due to being less strikingly developed than at Bisbee.

CHEMISTRY OF THE CHANGE.

The hypogene limestone ores of the Bisbee district consist of chalcopyrite, bornite, pyrite, sphalerite, occasionally a minor amount of galena, and the gangue, minerals of quartz, calcite, feldspar, sericite, and chlorite. Some manganese bearing material is also present.

Supergene smithsonite ores that result from the oxidation of sphalerite have been studied in detail by Loughlin,[6] Knopf,[7] and other writers. In summary, Loughlin's study proves that the sphalerite is attacked by oxidizing supergene solutions forming zinc sulphate, which being readily soluble, migrates with the solutions. When the limestones have depleted the free sulphuric acid and ferric sulphate, the zinc sulphate reacts with the limestone, replacing it by the relatively insoluble zinz carbonate; the calcium sulphate formed passes off in the ground water. To a lesser extent, smithsonite is deposited directly from solution by some precipitant or by evaporation. The genesis of siderite at Bisbee is essentially comparable to the genesis of smithsonite at Leadville;

[6] *Op. cit.* See also U. S. Geol. Surv. Prof. Paper 148. Also "Lime Carbonate and Related Copper Carbonate Ores at Ophir, Utah," U. S. Geol. Surv. Bull. 690, G. F. Loughlin, 1919.

[7] *Op. cit.*

iron and copper-iron sulphides oxidize, yielding ferrous iron sulphate which replaces the surrounding limestone, forming siderite and calcium sulphate. Simultaneously, or as a second step, the remaining limestone is removed by sulphuric acid solutions.

In detail, however, there are numerous modifying factors. It has been shown [8] that while ferrous sulphate reacting with limestone will yield siderite (ferrous carbonate), the ferric sulphate yields ferric hydroxide. To form siderite, then, there must have been a marked change in the solutions, which were relatively rich in ferric sulphate during oxidation of the sulphides and became low in ferric and rich in ferrous sulphate during formation of the siderite. Lindgren,[9] in discussing the work of Nishihara,[10] describes this as a normal downward change in mine waters: "Near the surface the mine waters are solutions of sulphuric acid and ferric sulphate; in depth their acidity decreases and ferrous sulphate increases; at greater depth the waters become neutral and finally alkaline."

The thorough oxidation of pyrite yields ferrous sulphate and sulphuric acid, the oxidation of the former being somewhat retarded [11] by the latter. Furthermore, the presence of cupric sulphate in the solution tends to accelerate the rate of oxidation of ferrous iron. Hence, physical conditions of rock fracturing, water level, and gangue minerals being the same, the chances of forming a siderite body rather than a limonitic body are greater in the case of pyrite than for chalcopyrite or bornite.

Nevetheless, large siderite bodies can form and do form beneath pyritic copper ore bodies in the Bisbee district under the following conditions. The hypogene sulphide bodies of Bisbee

[8] "The Data of Geochemistry," F. W. Clarke, U. S. Geol Surv. Bull. 770, p. 581. See also Knopf, *op. cit.*

[9] W. Lingren, "Mineral Deposits," pp. 855, New York, 1919.

[10] G. S. Nishihara, "The Rate of Reduction of Acidity by Descending Waters," ECON. GEOL., vol. 9, 1914.

[11] "Acceleration of Rate of Oxidation of Ferrous Iron in Presence of Copper, and Its Application to 'Heap Leaching Process,'" E. Posnyak, *Trans. A. I. M. E.*, 1927.

"Notes on the Oxidation Products Derived from Chalcopyrite," Roland Blanchard and P. F. Boswell, ECON. GEOL., vol. 20, No. 7, p. 615, 1925.

"Leached Outcrops as Guides to Copper Ore," Augustus Locke, Baltimore, 1926.

are very pyritic, frequently containing from 20 to 40 molecules of pyrite to one of chalcopyrite or bornite. Part of the sulphuric acid from the oxidation of this pyrite is used in neutralizing the associated gangue, and part attacks other sulphides, but because of the large amount of pyrite, there is a considerable excess of acid. Oxidation of chalcopyrite or bornite will yield cupric sulphate, ferrous sulphate, and some sulphuric acid. Most of the cupric sulphate reacts with the pyrite, chalcopyrite or bornite to form chalcocite; as an intermediate step, some of the cupric sulphate may be reduced by the ferrous sulphate, resulting in the relatively insoluble ferric sulphate and the unstable cuprous sulphate. Lindgren[12] states that: "Cupric sulphate is present all along but the secondary sulphides are not readily precipitated all the presence of much ferric sulphate though they are normally found in the presence of ferrous sulphate of slight acidity."

FIG. 4. Copper Sulphide Breccia Cemented by Siderite.

Also:[13] "Chalcocite probably reduces the ferric sulphate to ferrous." Because of the acidity of the solutions and possibly the reducing action of chalcocite, the ferrous sulphate is not oxidized to ferric sulphate but is free to pass into the ground waters and replaces the adjacent limestone.

[12] *Op. cit.*, p. 855.
[13] *Op. cit.*, p. 907.

Simultaneously, or just subsequent to the formation of the initial siderite, the sulphuric acid in the waters attacks the limestone between the siderite plates, forming calcium sulphate (which is mostly carried off in solution), water, and carbonic acid gas.[14] The rôle (pressure, concentration) played by the CO_2 is not fully understood and must be left for the experimental geochemist to investigate. It seems probable, though, that the liberated CO_2 and the water combine to form carbonic acid, which unites with the ferrous sulphate to form siderite and more sulphuric acid. This reaction may explain the origin of the siderite formed in the absence of any limestone, *i.e.*, siderite cementing the crushed boxwork siderite (Fig. 2) and siderite cementing brecciated fragments of hypogene copper-iron sulphides (Fig. 4). Some of the early siderite may go into solution as such and be redeposited as the cementing materials mentioned above, for ferrous carbonate is abundant [15] in certain mine waters.

The above reactions are believed to have taken place at and below the surface of the water table. In the Bisbee district this shows very marked variation in elevation in different sections of the mine depending upon the character of the rock and the degree of fracturing, and is subject to marked fluctuations depending on the season of the year and amount of rainfall. At the place of siderite deposition, conditions would at most be only slightly oxidizing (except along strong break zones where there might be an abnormal supply of oxidizing waters) and as a result, the ferrous sulphate and acid solutions would have unimpaired opportunity to attack the water-soaked limestone. The writers have not yet observed any instances of supergene siderite or smithsonite boxwork replacing dolomite, but it seems probable that such occurrences will be found.

[14] This apparent lag in the action of the H_2SO_4 and $FeSO_4$ may be the result of:— (1) the acid waters penetrating deeper as a result of increased porosity after the initial replacement of the limestone; (2) a slight general lowering of the water level due to tilting of the land or reduced rainfall, etc.; or (3) it may be a natural lag in the formation of the sulphates and their flooding of the surrounding rock during the chalcocitization process.

[15] F. L. Ransome, U. S. Geol. Surv. Prof. Paper 62, 1908, quoted by Lindgren, *op. cit.*, p. 902.

In the less pyritic ore bodies there will be (under similar physical conditions of rock and water table) more intense oxidation of the iron sulphate solutions because of the higher ratio of copper to iron in solution and also the relatively low ratio of sulphuric acid to ferrous sulphate. Very dilute solutions resulting from the oxidation of pyrite will yield goethite [16] rather than ferrous compounds. Consequently, from the oxidation of ore bodies low in pyrite there are found areas of limestone flooded by limonitic material adjacent to the ore body. This is particularly true in the Southwest mine at Bisbee; here, however, an added factor is the location of this ore body, well above the normal water table.

To sum up: Hypogene iron and copper-iron sulphides replace areas of limestone to form the primary ore-bodies of the Bisbee district. As oxidation starts, supergene iron solutions emanating from these ore-bodies form the boxwork siderite in underlying limestone. Therefore the boxwork is used as a guide to overlying oxidizing sulphide bodies.

BISBEE, ARIZONA.

[16] "The System, Fe_2O_3–SO_3–H_2O," E. Posnjak and H. E. Merwin, *Journal of American Chem. Soc.*, vol. XLIV., No. 9, p. 1991, Sept. 1922.

FURTHER STUDIES OF THE ORIGIN OF THE WABANA IRON ORE OF NEWFOUNDLAND.[1]

A. O. HAYES.

INTRODUCTION.

THE object of this article is to bring attention to observations made in 1927 indicating that the Wabana iron ore during the process of formation was exposed to oxidizing conditions in a very shallow marine basin that was exposed to the air over wide areas at low tide.

A detailed description of the ore deposit by the writer was published in 1915,[2] and mention of the observations described herewith was made in an article published [3] in 1928, entitled "Wabana Iron Mines and Deposits, Newfoundland."

The commercial importance of the deposit is indicated by the production of 1,500,000 tons of ore in 1928 and a project of about the same amount in 1929. Although it is impossible to prove the total amount of recoverable ore reserves, due to their submarine position, the stratigraphical and structural features of the deposit are such that a continuation of mining operations on as large a scale as practicable may be planned with confidence.

CHARACTER OF THE ORE BEDS.

Six ferruginous zones have been found in a thickness of 1,500 feet of strata exposed on Great Bell Island, and there is also a lean iron silicate bed underlying these on Kelly Island. There may be more beds, but most of the underlying strata are covered by the water of Conception Bay. Three zones in the upper 500 feet of

[1] Presented before the Society of Economic Geologists, New York Meeting, Dec., 1928.

[2] Memoir 78, Geol. Survey of Canada.

[3] *Mining and Metall.*, August, 1928.

strata each contain workable beds which are now being mined, called the Lower, Middle and Upper beds.

Included with the workable ore beds within this thickness of 500 feet of sandstone and shale strata are some 60 beds of hematite varying in thickness from a fraction of an inch to 23 feet.

All the ferruginous beds obey the same laws of sedimentary accumulation as do the enclosing sandstone and shale layers. They thicken and thin, due to wave and current action as shown by cross bedding and ripple markings.

The minimum thickness for economical mining is about four feet, and three of the beds, known from their surface outcrop, have proved remarkably persistent and extensive. The maximum thickness so far discovered is in a portion of the Lower bed in the submarine working where 23 feet of nearly solid ore is mined. Fifty thin beds underlie this workable bed, showing that the conditions of the formation of the iron were approaching perfection for a long period of time, before their culmination.

Well preserved rain-drop impressions are found 100 feet below the lowest hematite bed of this zone, and also in the sandstone foot wall of the Lower bed. This condition shows that the ore was subject to oxidation in very shallow water and more probably either was actually exposed to the air between tides, or in lagoons in which the water level frequently fluctuated sufficiently to expose the sediments to the air at intervals.

Since the ore strata contain marine fossils, such as brachiopods and trilobites, which lived in shallow water, exposure by tides seems reasonable. A change to oceanic conditions is proved for the strata above the Lower bed by the presence of graptolites, a fauna of plankton carried about by open ocean currents. It is therefore evident that subsidence of the shallow water iron oxide deposits took place at the close of the deposition of the Lower bed. This is confirmed by an overlying deposit of oölitic iron sulphide free from iron oxide, which also contains abundant graptolites.

THE ORE MINERALS.

There is an observed basis of fact for the conclusion that the mineral chamosite, a hydrated silicate of iron, was deposited directly from the Ordovician sea water but there is only inferential evidence for the primary origin of the hematite which forms 60 per cent. of the ore. The chamosite forms about 23 per cent. of the ore.

The mineralogical character of the ore is shown in the following table:

Name of Mineral.	Chemical Composition of Mineral.	Per Cent.	Lower Bed, Average No. 2 Mine.	Lower Bed, Average No. 3 Mine.	Lower Bed, Average No. 4 Mine.	Average No. 6 Mine.
Chamosite (green hydrous silicate of ferrous iron, alumina, and magnesia, in the proportions shown in the next column)..	SiO_2	25.64	.....	.....	.....	.....
	Al_2O_3	19.75	.....	.....	.....	.....
	FeO	39.74	22.78	23.49	23.29	22.68
	MgO	2.98	.....	.....	.....	.....
	H_2O	11.89	.....	.....	.....	.....
Hematite.....	Fe_2O_3	.....	62.86	60.77	61.38	54.77
Siderite.....	$FeCO_3$	.....	2.82	2.53	3.34	13.34
Quartz (sand grains)	SiO_2	.....	5.558	6.276	6.468	3.614
Calcium Phosphate (from shell fragments).....	$(CaO)_3P_2O_5$	.....	4.71	4.866	3.622	4.408
Calcite (filling cracks and fault fissures in the ore).	$CaCO_3$	.....	1.05	0.55	0.87	1.25
Manganese oxide...	MnO_2	.....	0.25	0.27	0.30	0.33
Titanic acid.....	TiO_2	.....	0.35	0.35	0.33	0.37
Iron pyrite.....	FeS_2	.....	0.097	0.103	0.083	0.103
Total.....			100.49	99.20	99.68	100.26

The ore is oölitic. The spherules or concretions vary from one-tenth to one-half of a millimeter in diameter and examined in thin section under the microscope are seen to be composed of concentrically arranged layers of hematite, chamosite, and more rarely calcium phosphate, in an onion-like structure.

The hematite is so opaque that the concentric concretionary structure is apparent only in the leaner silicate ore. The iron carbonate (siderite) is secondary to the spherules, and has locally

replaced the chamosite and the hematite and has not been observed as an original constructive element of the spherules.

ORIGIN OF THE HEMATITE.

A conglomerate of pebbles of oölitic hematite and chamosite in a matrix of black shale occurs locally at the top of the thick Lower bed, confirming again the conclusion that the oölitic iron ore was an original sediment, and the hematite was formed before the consolidation of the rocks.

The method of formation of the iron oxide is not so clearly established. The chemical composition of the ore suggests that it may have been precipitated directly from the sea water, but there are more examples of the formation of silicates of iron in salt water than of oxides, and so the possibility of oxidation of the chamosite as a source for the large amount of hematite needs study.

If all the oxide came from chamosite, which contains 25 per cent. silica, a larger amount of silica would be expected in the ore, in fact about four times the amount contained, and it would be necessary to conclude that the residual aluminous silicate was eliminated in some way, either chemical or mechanical.

This aluminous silicate would probably have been a flocculent material easily removed by flotation, and perhaps the silicate parting rocks frequently found interbedded in the ore may be partly made up of such material.

Secondary silica occurs locally both in the ore beds and in the oölitic pyrite beds, usually in crystalline form interstitial to the spherules, and may be derived from the chamosite by solution and reprecipitation.

No solution of this problem has come to the writer's notice, and a conclusion must await further study. The writer thinks that some of the hematite is secondary after the chamosite, and some was precipitated directly.

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ORIGIN OF CHROMITE DEPOSITS.

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INTRODUCTION.

CHROMITE, whether it occurs as an abundant accessory mineral or as a deposit of commercial importance, is restricted to the ultrabasic rocks or their derivatives. The alteration products of the ultrabasics may be serpentine, talc, or carbonate.

The occurrences of chromite are chiefly in the form of pockets or lenses; in schlieren, which are usually much longer than broad; in disseminated deposits; and in chrome sands, which have accumulated in watercourses, owing to the mechanical concentration following the disintegration of a chromiferous rock. The ore bodies vary in size from small, isolated pockets or "pots" as illustrated at Bare Hills, Maryland, and Hestmandø, Norway, to larger masses containing many thousand tons, as at the famous Wood Mine, Lancaster County, Pennsylvania, the Castle Crag Mine, Dunsmuir, California, and the Great Dyke and Selukwe deposits of Southern Rhodesia.

Opinions in regard to the relations between the periods of crystallization of chromite and the groundmass minerals are

divergent. Some investigators have regarded chromite as the earliest constituent to crystallize but other have shown evidence that chromite may form at later periods. The study of chromiferous rocks from the important chromite regions of the world has yielded abundant evidence that much chromite is formed during the late magmatic period. The writer has recognized three distinct periods of crystallization of chromite: (1) Chromite of the early magmatic period is the first mineral to crystallize. An overlap in the periods of crystallization of chromite and olivine is often noted; (2) Chromite of the late magmatic period is later than the groundmass minerals and occurs in zones of crushed olivine, in cleavages of the cleavable minerals and as replacements of the earlier pyrogenic silicates of the groundmass; (3) Chromite of the hydrothermal period is definitely later than the pyrogenic silicates and is associated with deuteric minerals; the chromite of this period was formed by either early or late hydrothermal solutions.

The writer takes this opportunity to express his gratitude to all those who have contributed materials for this study and to Professor Joseph T. Singewald, Jr., who outlined and supervised the problem.

DESCRIPTION OF CHROMITE ORES.

Chromite in Thin Section.

Form.—Chromite, in thin section, shows varying degrees of perfection of crystal form. In unaltered rocks chromite of early magmatic origin is usually characterized by lack of fracturing. Forms may be euhedral and subhedral. The subhedral forms probably originate through corrosive action by the solutions that carried the constituents that formed the groundmass minerals. Chromite of the magmatic period is invariably in small grains, occurring either singly or in aggregates. Vogt has applied the term "synneusis structure" (together-swimming) to such accumulations (Fig. 1). Bowen[1] does not accept Vogt's view that such accumulations are caused by an attraction of one crystal for

[1] Bowen, N. L., "The Evolution of Igneous Rocks." Princeton University Press, 1928.

another, but suggests that they are due to a sort of pseudomorphism after a resorbed mineral.

Euhedral grains of chromite, embedded in a groundmass of enstatite or bastite, may show a structure similar to that of the chondrules of meteorites. Anhedral forms are more predominant than euhedral and subhedral types. They may or may not be fractured. Diller [2] believed that anhedral forms crystallized under conditions of interference. Solution of original euhedral grains by late magmatic or early hydrothermal solutions is believed, by the writer, to be equally responsible for the development of such forms. Small apophyses of chromite thus developed from the original grain may penetrate groundmass minerals.

Fracturing.—Fracturing of chromite grains is more pronounced in the hydrothermally altered ultrabasic rocks than in the fresh varieties. Incipient fractures serve as solution channels and the force of crystallization of later materials within these channels may split off peripheral portions of the grain or pass completely through the chromite. Fracturing may be more or less regular and produce a "mitred-structure." This term is applied to those grains which have been fractured in such a way that the removal of the material deposited in the fracture would allow dovetailing of the adjacent parts of the chromite.

Color.—Chromite commonly shows translucency in tones of yellowish brown through orange brown to deep cherry red. Some grains are black and show no translucency even on thin edges. A peculiar color phenomenon has been noted by the writer and others. The central portion of a chromite grain may be yellow-brown by transmitted light, although a continuous or discontinuous black border may surround the translucent center. Black opaque lines may traverse the entire grain without respect to cleavage, fracture or outline of the chromite. Dresser [3] noted this peculiarity in Canadian chromite specimens and found that

[2] Diller, J. S., "Recent Studies of Domestic Chromite Deposits," Am. Inst. Min. Eng. Bull. 153, 1919, pp. 2018 et seq.

[3] Dresser, J. A., "Preliminary Report on the Serpentine and the Associated Rocks of Southern Quebec," Can. Geol. Surv. Mem. 22, 1913.

the opaque portion was richer in ferric iron and poorer in chromic oxide than the translucent center. Phillips[4] observed the same features in chromite of the Shetland Islands, and favored the view that the black material was grown upon earlier-formed chromite. Lewis observed the same features in the North Carolina occurrences. The association of penninite with chromite grains showing this color phenomenon led him to the conclusion that alumina and magnesia were subtracted from the peripheral portion of the chromite to form the penninite sheath. This subtraction caused a relative increase in the ferric iron content of the peripheral zone of the chromite and opacity resulted. An examination of Lewis' slides by the present writer shows that there is no relationship between the zoning of colors in the chromite and the associated groundmass minerals. Solution of chromite is indicated in many cases. The writer favors the view that these black lines represent deposition of ferric oxide, possibly as a cement, along narrow or incipient fractures in the chromite.

The common colors noted in chromite grains are yellowish brown, yellowish red, reddish brown, coffee brown, cherry red and black. Analyses of ore specimens compared with thin sections from the analysed material indicates that the lower the content of chromic oxide the more yellow the color of the chromite becomes. High chromic oxide content is commonly indicated by shades of deep cherry red. There is no apparent correlation between the black chromite grains and their chemical analyses. Separation of chromite, from the associated groundmass minerals, by means of heavy liquids, indicates that the mineral association of the chromite is in no way connected with the chemical composition of the ore mineral.

Minerals Associated with Chromite.

The most important common associate of chromite is serpentine. Johannsen[5] lists 16 varietal serpentines and separates

[4] Phillips, F. C., "The Serpentines and Associated Rocks and Minerals of the Shetland Islands," *Quart. Jour. Geol. Soc.*, 83, 1927, pp. 622–652.

[5] Johannsen, Albert, "The Serpentines of Harford County, Maryland," Md. Geol. Surv. 12, 1928, p. 242.

them on the basis of their occurrence as massive, lamellar, or fibrous forms. Minor differences in structure and texture have led to this multiplicity of names, which is entirely uncalled for. The writer limits his use of descriptive names to the four most common types of serpentine that are recognizable macro- and microscopically. These are:

Antigorite.—This is commonly developed from olivine, the alteration beginning along fractures and preserving the characteristic mesh structure superimposed by the network of fractures. The stated pleochroism of antigorite is accidental rather than essential and has seldom been noted by the writer.

Bastite.—This mineral commonly forms pseudomorphs after enstatite and is easily distinguishable from the other serpentines on the basis of parallelism of its fibers. Interlocking fibrous zones are developed in completely serpentinized enstatites. If diallagic parting has been superimposed on original enstatite grains it will be reflected in the inclined extinction of the zones of bastite.

Williamsite.—This apple green to jade green, translucent variety of serpentine is characteristic of the Line Pit (State-Line Serpentine Belt). It appears fibrous and closely resembes antigorite but has higher interference colors. The arrangement of the fibers or plates suggests enstatite as the original mineral.

Chrysotile.—This is the fibrous form of serpentine, with fibration normal to the enclosing walls of the thin veinlets in which it usually occurs. It also resembles antigorite but is characterized by delicate fibers that show positive elongation.

Chlorites.—One is rarely able to distinguish between kämmererite, a chlorite, and kotschubeite, a clinochlore, in the hand specimen. Penninite is determined with equal difficulty. Kämmererite may be developed in large, well-defined, micaceous forms. It is colorless in thin section and lacks the pleochroism ascribed to it by Weinschenck and others. Penninite is denominated by anomalous lavender blue interference colors and kämmererite shows abnormal colors, commonly deep blue to rust brown. Kotschubeite has much lower birefringence than kämmererite, shows marked pleochroism and is always negative in character.

Stichite.—This mineral is reported from Dundas, Tasmania. Specimens of the material were sent the writer by Blake; these show a light strawberry pink to a pale lilac colored incrustation on compact, fine-grained serpentine. Stichite is a complex hydrous magnesium carbonate with chromic oxide, and resembles brugnatellite chemically. Optically it is closely related to kämmererite although it is easily distinguishable from the chlorite on the basis of the radial arrangement of fibers, which are invariably grouped about a center or nucleus that is commonly an anhedral chromite. Chrysotile often shows the same mode of occurrence as stichite and it is suggested that stichite is formed as a pseudomorph after chrysotile.

PARAGENETIC RELATIONS OF CHROMITE.

The present study of specimens from many localities brings out the fact that much of the chromite is of primary crystallization and that it is of both early and late magmatic origin. There is evidence of solution and redeposition of this chromite by hydrothermal processes. It is difficult to draw a sharp line between deposits that are strictly magmatic segregations and those that have been formed largely by hydrothermal solutions.

A comparative study of the chromiferous rocks was made in order to ascertain whether there is any decided difference in the mode of occurrence of chromite in rocks which show varying degrees of metamorphism.

In Fresh Rocks.

Chromite of the fresh rocks is usually characterized by lack of fracturing. Euhedral and subhedral forms may be present. The essential minerals of the fresh rocks are olivine and enstatite in varying proportions.

Alaska.—Chromite occurs as unfractured, subhedral grains in zones of crushed olivine in the comparatively fresh dunite of Claim Point. The olivine grains of the groundmass are elongated and granulated. Wavy extinction of olivines is noted. The chromite is unfractured and represents a product of late magmatic

origin that was formed after the processes that caused granulation and elongation of the olivines had died out. That chromite was formed after the olivine is indicated by several features: (1) unfractured chromite occurs in highly fractured olivines; (2) outlines of chromite grains transect olivine boundaries; (3) apophyses of chromite are developed in the cleavages of monoclinic pyroxenes (Red Mountain Area); and (4) chromite in finely granulated olivine is unfractured.

New Zealand.—The chromite deposits of New Zealand occur as impregnations and streaks in the ultrabasic rocks of the upper basin of Takaka river, 30 miles northwest of Nelson. The original dunite of von Hochstetter is from this general locality.

The New Zealand rocks, studied by the writer, are practically unaltered dunites in which chromite occurs as ill-defined streaks that show mitred-structures. The boundaries between the chromite grains and adjacent olivines suggest contemporaneity of crystallization of these two minerals. Kelyphitic rims of chrysotile are developed around the chromite grains and show no staining by chromiferous solutions. There are quite a few veinlets of chrysotile traversing the groundmass minerals, and chromite in elongated grains between the fibers of such veinlets is the only evidence of chromite of late crystallization.

Although the chromiferous rocks of New Zealand and of North Carolina bear striking resemblances, it is to be noted that in the former locality serpentinization and chloritization are not prominent features.

Other Localities.—Chromite occurs interstitially between olivine grains in the fresh dunite of Balsam Gap, North Carolina, and between olivine and enstatite grains in the unaltered peridotite of Selma, Oregon. Euhedral grains of chromite transect large olivine crystals embedded in a trachytoidal groundmass of bytownite-anorthite in the peridotites of the Isle of Skye.

The chromite of the fresh rocks described above is undoubtedly of late magmatic origin.

In Hydrothermally Altered Rocks.

The chromiferous ultrabasic rocks are composed almost entirely of mafic minerals. The occurrence of this type of mineral is conducive to rapid, and, in places, complete alteration. Olivine is, perhaps, the predominant mineral of the ultrabasics. It is unstable under ordinary conditions of weathering so that its presence in large amounts is a causative factor of alteration. The most common processes of alteration noted in the study are: (1) serpentinization, (2) chloritization, (3) talcization and (4) hornblendization.

The chromite of hydrothermally altered rocks may or may not be fractured but the outlines of the grains are more predominantly anhedral. Chromite that was deposited by the hydrothermal solutions that produce such minerals as talc, tremolite, actinolite, anthophyllite, serpentine, chlorite and magnesite is termed hydrothermal chromite. Much of this type of chromite might have resulted from the solution and redeposition of chromite of the magmatic stage.

Hydrothermal amphiboles, chlorites and talc are well developed in the chromiferous rocks of Norway and North Carolina. The suite of minerals in each of these areas is practically the same. Penninite, anthophyllite, actinolite, talc, calcite and serpentine are the typical minerals associated with the deposits of these two areas, although serpentine is developed in very minor amounts.

Norway.—The original saxonitic rocks of Hestmandø, Norway, have been altered to an advanced stage by hydrothermal solutions. Calcite, talc, actinolite and penninite have been formed. Calcite replaces olivine in many of the examples studied. Olivine relicts are included within the enstatites and suggest that the former mineral has been replaced by the latter. In practically all the thin sections of the Norwegian chromiferous rocks, which were sent the writer by Professor J. H. L. Vogt, there is evidence of solution of chromite and its redeposition either contemporaneous with, or subsequent to, the formation of the deuteric minerals.

In the Selsovik area the same suite of minerals has been developed. Elongated grains of chromite of late magmatic origin

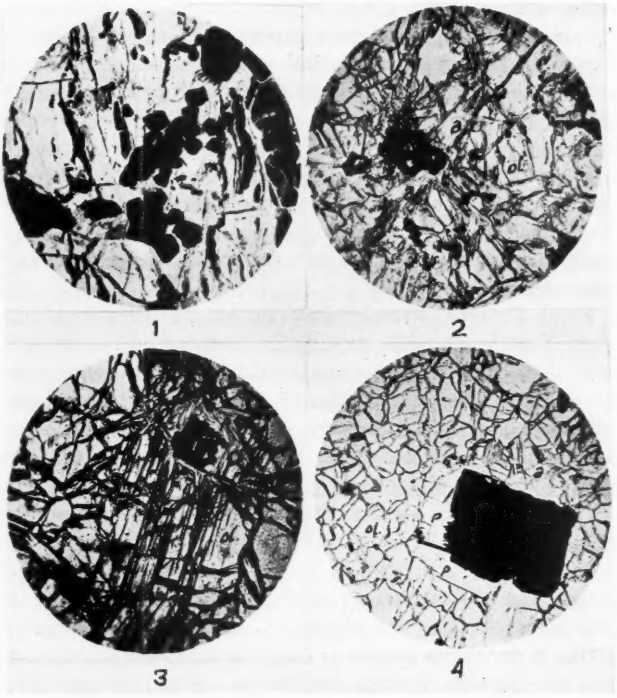

FIG. 1. Euhedral and subhedral grains of chromite in accumulative structures—"synneusis"—occurring in a bastitic groundmass. Dark gray (right) limonitic stain on bastite. Rhodesia. × 12.

FIG. 2. Chromite grain penetrating actinolite (*a*) blade. A thin sheath of talc (*t*) surrounds chromite. Olivine groundmass (*ol*). Norway. × 12.

FIG. 3. Subhedral grain of chromite completely sheathed by penninite (*p*) in an olivine (*ol*) groundmass. The groundmass is practically fresh. Webster, North Carolina. × 12.

FIG. 4. Subhedral grain of chromite with an apophyse injected into penninite (*p*) plates. Actinolite (*a*) and olivine (*ol*). Burnsville, North Carolina. × 12.

occur between olivine grains, in the fractures of olivine and in the cleavages of enstatite, and across the cleavages of the deuteric minerals. In Fig. 2 an anhedral chromite grain penetrates an actinolite blade which is optically continuous on each side of the chromite. A thin sheath of talc separates the chromite from the actinolite.

Chromite of the late magmatic stage is more abundant in the Norwegian occurrences than that of the early magmatic. Hydrothermal chromite, developed in cleavages of penninite, enstatite and actinolite is also of greater importance than early magmatic chromite.

North Carolina.—The greatest amount of alteration of the North Carolina chromite deposits has been caused by chloritization. The chromite masses are invariably associated with penninite and with talc. The manner of association of the hydrothermal minerals with the chromite suggests a genetic relationship between these minerals. Some black chromite grains are completely enclosed in penninite (Fig. 3). Thin, elongated apophyses of chromite project from the original grain into the cleavages of the penninite as is illustrated in Fig. 4.

Another thin section shows a penninitic zone in contact with fresh olivine. The character of the boundary indicates that the chlorite has replaced the olivine. Chromite grains are nearly lacking in the olivine portion of the groundmass and in the penninitic zone near the contact. Beyond the contact, however, chromite is abundant in the penninite. Subhedral, unfractured forms predominate and cut across the cleavages of the chlorite plates or penetrate between them. The penninite zone represents solution along a fracture. The chromite deposited was carried in solution by the hydrothermal waters that replaced olivine with penninite.

The chlorite in the North Carolina rocks varies between kämmererite and penninite. Specimens from Webster show kämmereritic zones similar to the penninite zones described above. A thin veinlet of magnesite is developed in such a kämmererite zone. The only chromite in the zone is a discontinuous streak

of euhedral grains parallel to the magnesite veinlet. It was deposited by the solutions that deposited the magnesite.

The almost invariable development of either talc sheaths or penninitic zones around the chromite of North Carolina is indicative of a genetic relationship between the chromite and the deuteric minerals. A small portion of the North Carolina chromite is regarded by the writer as representing chromite of the early magmatic stage. Most of the chromite of the North Carolina deposits is of hydrothermal origin.

Pennsylvania.—The original chromiferous rocks of the State-Line serpentine belt of Pennsylvania and Maryland were saxonites, dunites, wehrlites and websterites. Thus they resemble the Norwegian and North Carolina rocks chemically. Serpentinization, however, has been the dominant process of alteration in the State-Line belt. The hydrothermal minerals described in the preceding areas are almost entirely lacking in the serpentines of Pennsylvania.

The best example of chromite associated with penninite is from the famous Wood Mine, Lancaster County, Pennsylvania. According to Glenn,[6] "the Wood mine stands alone among chrome mines. It is truly an ore shoot, a vein, as are the copper mines in the crystalline rocks at Capelton, in the province of Quebec, or at Ely, or at Elizabeth in Vermont." Glenn also stresses the smooth and well-defined footwall.

Deweylite and magnesite fill small fractures which extend radially for half an inch into the serpentine surrounding the chromite. These minerals originated during the period of hydrothermal activity. The rocks on the dump carry clinochlore, kämmererite, uvarovite, zaratite, deweylite, brucite, magnesite and hydromagnesite.

Chromite of the Wood mine is characteristically black in color, although translucent reddish brown and yellowish grains are not uncommon. The ore mineral occurs as disseminated particles in serpentine. Bastite and antigorite are abundantly developed and

[6] Glenn, William, "Chrome in the Southern Appalachian Region," *Am. Inst. Min. Eng. Trans.*, 23, 1895, p. 481.

indicate that the parent rock was a saxonite. Penninite is seen in some of the slides, and wherever this mineral is developed in abundance chromite veinlets or stringers of considerable size are associated with it. Fig. 5 shows such a veinlet of chromite in penninite. The chromite veinlet is separated sharply from the olivine by a selvage of penninite. No penninite is developed in the olivine groundmass, and chromite occurs but sparingly in the olivine.

In other slides from the same mine much chromite is associated with the hydrothermal bastite and magnesite as shown in Fig. 6.

Much of the chromite of the Wood Mine is late magmatic, although considerable hydrothermal chromite was brought in by the same solutions that penninitized and serpentinized the original rocks.

California.—Outcrops of magnesian rocks are abundant along the Pacific Coast. California has been the most important chrome ore producer in the western United States. The belt of chromiferous rocks, which is best developed in San Luis Obispo, Alameda, Placer, Glenn, Tehama, Siskiyou and Del Norte counties, California, passes into the Blue Mountains of Josephine and Curry counties, Oregon.

The California studies by the writer were based largely on the thin sections of specimens from the Castle Crag Mine, Dunsmuir, Shasta County, which were used by Diller in his descriptions of the California deposits. The ore occurs as disseminations in pyroxenite, dunite and saxonite, Serpentinization has been the chief type of alteration of these ultrabasics. Diller [7] arrived at the conclusion that in most cases the crystallization of the chromite antedated that of the silicates and that the mutually interlocking anhedral boundaries of the chromite and the silicates, indicates, at most, contemporaneity of the periods of crystallization.

The writer's conclusions regarding the Dunsmuir deposits are not fully in accord with those of Diller and are as follows:

[7] Diller, J. S., "Chromite in the Klamath Mountains, California and Oregon," U. S. Geol. Surv. Bull. 725, 1921.

1. The presence of elongated masses of chromite with irregular boundaries against enstatite indicates that the former mineral penetrated fractures and replaced, in part, the enstatite.

2. Where associated with olivine rocks, the chromite invariably shows anhedral to subhedral forms, and not subhedral to euhedral forms, as suggested by Diller. Tongues of chromite have replaced original olivines.

3. The relations of chromite to olivine are distinctly those of replacement, and the bordering rims of serpentine indicate that the chromite was deposited by the same hydrothermal solutions that caused serpentinization.

4. Where chromite occurs in partially serpentinized rocks it is not in the olivine but is sheathed by a zone of serpentine. This feature recalls the penninite sheaths of the North Carolina deposits. It is not likely that serpentinization could affect only the contacts between chromite and olivine. The relations suggest that the chromite was deposited when the serpentinization occurred.

5. Where the chromite is associated with penninite, there is a definite relationship between the elongation of the penninite shreds and its outlines. This suggests that the chromite postdates the penninite. The alternate view, however, that the chromite might have replaced the enstatite prior to the development of the penninite, is not overlooked.

Nodular chromite is typical of the deposits of New Castle, Eldorado county. Some of the specimens show a nodular chromite surrounded by a thin sheath of tremolite, and in others, definite banding of chromite has occurred in a completely carbonated rock. Where tremolite is developed it is invariably restricted to areas of chromite and suggests a genetic relation between the tremolite and the chromite.

The chromite deposits of California show all gradations from chromite of late magmatic origin to hydrothermal origin, the latter type being definitely associated with the serpentinization of the ultrabasics.

Oregon.—Westgate [8] outlines in brief the geology of the Baker and Grant counties chromite deposits. In discussing the origin of the chromite, Westgate eliminates the idea of origin due to circulating waters after solidification. He believes that the chromite and the silicates belong to the same general period of formation and that subsequent movements in the serpentine, due to volume increases, are responsible for the shape of the ore bodies. Finally, Westgate is unable to decide whether the chromite is due to early crystallization of the more basic minerals or whether it was introduced toward the end of the period of solidification after the main mass of the body was substantially solid.

The writer's study of specimens from Sexton Peak, Josephine County, and from Mormon Basin, Baker County, leads him to the conclusion that much of the chromite occurs as a replacement of the groundmass minerals and is, therefore, of late magmatic origin.

Washington.—A study of the chromiferous rocks of the Cypress Island and Mt. Hawkins areas shows that the origin of these deposits is different from that of the California and Oregon deposits. The original rocks of both areas were strongly dunitic in character, although the development of much bastite in the Cypress Island specimens indicates a rock more closely related to saxonite. The color and the general character of the chromite from these two widely separated localities do not vary greatly. The lack of euhedral form, and the occurrence of peripheral inclusions of olivine in the chromite together with the tonguing-out of chromite between olivine grains suggests a progressive overlap in the periods of crystallization of olivine and chromite. The major portion of the chromite is believed to have been well crystallized when olivine commenced to freeze, although there is evidence that the amount of chromite contemporaneous with, and later than, the olivine is not entirely insignificant.

Transvaal.—The chromite deposits of the Transvaal, located in the Bushveld Complex, are peculiar in that they are associated

[8] Westgate, L. G., "Deposits of Chromite in Eastern Oregon," U. S. Geol. Surv. Bull. 725, 1921, pp. 37–60.

with enstatite or hypersthene rocks (now serpentinized) and anorthosites. There are two separate chromite occurrences in the Transvaal, the Rustenburg and Lydenburg districts.

Rustenburg District: This district lies in western Transvaal. Chromite has been found at 12 localities in a more or less well-defined zone that has been traced for 28 miles. In some places the width of the ore outcrop is 30 feet.

Lydenburg District: This district lies in the eastern part of the Transvaal and the norite belt here reaches a maximum width of one and one half miles, outcropping almost continuously around the entire complex.

The principal chromite deposits are situated on the Grootboom farm and consist of two workings located on opposite sides of a spur. The lower portion of the Complex is the ore-bringer and it consists of bronzite and feldspathic bronzitite.[9] The character of the rocks and their sequence are indicative of a synclinal structure similar to that of the Great Dyke of Southern Rhodesia. A section, given by Wagner, follows:

600 Feet Nw. of No. 14 Adit, Mine No. 1.

Anorthosite with big crystals of diallage	
Coarse pegmatitic bronzitite	½ foot
Chromitite	½ inch
Anorthosite	4 to 8 in.
Chromitite	1 foot
Bronzitite	½ to 1 in.
Chromitite	7 inch
Bronzitite	½ foot
Chromitite	4 feet
Bronzitite	½ foot
Chromitite	1 foot
Footwall feldspathic bronzitite	
Aggregate thickness of chromitite seams	6 ft. 7½ in.

The chromite in thin section shows well developed crystal form. The color of the grains varies from a yellowish to reddish brown and no black grains have been noted in the specimens studied. Rounded phenocrysts of yellowish to brownish bronzite and diallage are literally "peppered" with small, euhedral chromites.

[9] Wagner, P. A., personal communication.

Chondrule-like structures are noted and in these a thick outer zone of chromite encloses fairly fresh enstatite or diallage. In other cases the chromite appears to completely envelope the pyroxene crystals. The gradual transition from pure ore to barren rock, and the petrographic study of thin sections indicate that the chromite is a product of the magmatic period and that the concentration in seams is probably due to gravitational differentiation.

Southern Rhodesia.—The Great Dyke of Southern Rhodesia is a basic intrusive younger than the rocks of the Bushveld Complex. The dike is approximately 300 miles in length and four miles in width. Synclinal structure apparently prevails in the dike in the vicinity of Makwiro. The marginal facies of the mass consist mainly of an altered and rotten harzburgite (saxonite). Above this basal harzburgite is a thin chromite-bearing serpentine which does not extend much further south than Makwiro. The serpentine is capped by a thick layer of pyroxenite which is, in turn, overlain by an equally thick feldspar-rich norite.

The rocks of the dike are composed in general of four essential minerals, enstatite, labradorite, olivine and augite, with accessory chromite and platinum. The variation in proportions of these four essential minerals has resulted in the formation of at least 15 distinct types of ultrabasic rocks. The predominating types are feldspar-rich norite, pyroxenite, harzburgite (saxonite) and serpentine.

Selukwe: Chromite occurs in this region in talc schists and serpentines which are associated with related carbonate rocks. The chromite-bearing rocks of the Selukwe complex are exposed in masses of irregular outlines, bordered by acid rocks, chief among these latter being the Mont D'Or granite.

Makwiro: Most of the writer's information regarding the paragenesis of the chromite ores of the Great Dyke was obtained by a study of a suite of rocks from the Netherfield farm, Makwiro. These rocks were sent the writer by H. B. Maufe, Director of the Geological Survey of Southern Rhodesia.

In the vicinity of Makwiro, a narrow and quite uniform strip

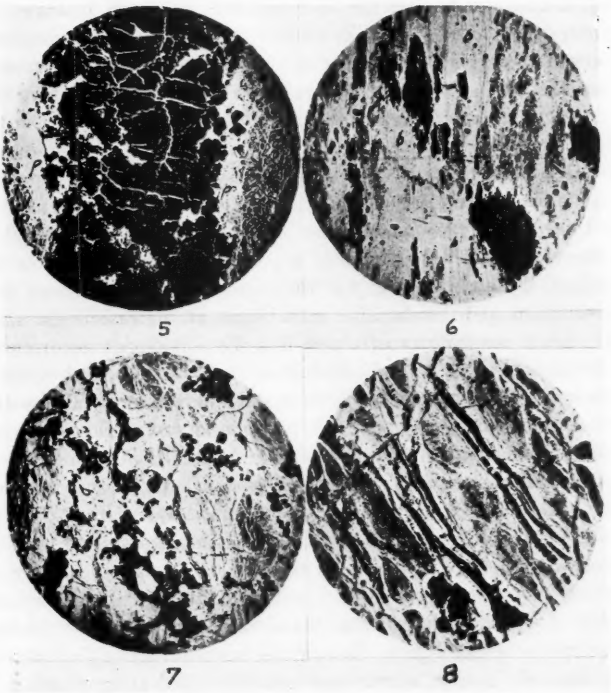

FIG. 5. A chromite veinlet bordered by penninite (*p*). The olivine groundmass on right side of veinlet does not show as much magnetite dusting as that on the left side. Wood's Mine, Pennsylvania. ×35.

FIG. 6. Chromite of late crystallization, with its longest dimension parallel to enclosing bastite (*b*) fibers. Darker gray material (*m*) is magnesite. Jenkin's Pit, State-Line Serpentine Belt. ×15.

FIG. 7. Chromite of late magmatic period occurring interstitially between enstatite (now bastitized). Rhodesia. ×15.

FIG. 8. Chromite of hydrothermal stage restricted to central portion of bastite zones. (This is from same slide as Figure 1). Rhodesia. ×15.

of harzburgite borders the dike on both sides and separates it from the granite mass. Tongues of chromite-bearing serpentine occur between the harzburgite and the overlying pyroxenite, and extend from north of the Hunyani river. The general trend of the serpentines, which lens out near Makwiro, is comparable to the harzburgite-granite contact. The pyroxenite, which overlies the serpentine, is capped by an equally thick feldspar-rich norite that forms the norite plateau.

Considerable bastite has been developed in the harzburgite. Chromite grains are grouped in aggregates in the bastite groundmass as illustrated in Fig. 7. The transitional phase between the harzburgite and the chromite seam shows an increase in the size of such accumulations of chromite. Two modes of occurrence of chromite are noted in the transitional rocks: (1) vein chromite, black in color, traversed by numerous thin fractures filled with serpentinous material, and (2) patches of rather closely compacted anhedral to subhedral grains of black chromite in bastite. Considerable chromite is developed in the bastite zones of the footwall and differs in color from the chromite of the veinlets and accumulations. Three types of veinlets are noted in the footwall rock: (1) parallel to the original enstatite cleavages, with tongues projecting into and parallel to fibration of the bastite (Fig. 8); (2) cutting across fibration of the bastite, which is normal to the cleavage of the original enstatite; and (3) thinner veinlets of chromite which have been developed along planes of movement which offset the first type. Chromite of the second type is undoubtedly later than the silicate minerals. Feathery edges and open-textured grains indicate that there has been abundant solution of the chromite. Such solutions deposited the hydrothermal chromite in the bastite zones.

A study of thin sections together with consideration of the form of the deposits of the Great Dyke leads to the conclusion that these chromite deposits represent accumulations of late magmatic origin. Keep[10] has endeavored to explain the alternation

[10] Keep, F. E., "Interim Report on the Geology of the Chromite Deposits of the Umvukwe Range, Lomagundi District," S. Rhodesia Geol. Surv. Short report, 23, 1928.

of layers of chromite with layers of barren rock as caused by processes analogous to oil flotation. Such a view is regarded as entirely untenable by the writer in view of the complete absence of evidence of vertical convection currents. Keep also believes that the formation of the synclinal structure of the dike has been caused by swelling of the rock due to serpentinization. It is difficult to visualize how a depressional type of structure might be produced by swelling of underlying rocks.

Insofar as the Great Dyke chromite deposits are concerned the writer is of the opinion that the larger masses of chromite are due to gravitational differentiation which took place during the late stages of magmatic segregation. Chromite of hydrothermal origin is confined to bastite and serpentinous products and chromite of late magmatic origin is now indicated by the gathering of crystals in accumulative structures determined by resorption of original groundmass minerals.

Australia.—Through the courtesy of Wm. Baragwanath, Director of the Victoria Geological Survey, the writer has been enabled to study specimens of the chromiferous rocks of Victoria. These rocks are highly altered and are almost completely serpentinized. The presence of much bastite suggests either enstatite or bronzite as the original mineral, but the peculiar mesh-like structure of the serpentine indicates that fairly large amounts of olivine also occurred in the original rock. Thiele,[11] in discussing the chromite of the Dolodrook area, says:[12]

> Chromite is recognized both as a secondary and an original constituent of igneous rocks, but it would appear that the Dolodrook occurrence most probably indicates a particularly fine example of magmatic segregation, in which olivine, pyroxene, corundum and chromite all represent different phases.

The writer is in accord with Thiele's views in general but suggests that other features are indicated. There is strong evidence of solution and redeposition of early magmatic chromite. Thiele

[11] Thiele, E. O., "Notes on the Dolodrook Serpentine Area and the Mt. Wellington Rhyolites, North Gippsland," *Roy. Soc. Vict., Proc.*, 21 (n. s.), 1907, pp. 249–267.

[12] *Idem*, p. 261.

is inclined to follow Pratt in arriving at his ideas of origin chiefly because of the association of chromite and corundum. The color of the chromite in thin section varies from translucent yellow picotite to the reddish or coffee brown chrompicotite. The two types are seen in the Victorian slides. Peripheral inclusions of bastite in the chromite indicate an overlap in the periods of crystallization of the enstatite and the chromite. Small, discontinuous stringers of chromite associated with fibers of brucite and bastite offer further evidence of solution of magmatic chromite and its redeposition under hydrothermal conditions.

New Caledonia.—Power [13] mentions that the chromite of New Caledonia occurs in masses in the joint planes of the serpentine. Because of this type of occurrence, and the fact that there is no sharp line of demarcation between ore and the enclosing serpentine, Power is inclined to regard the ore as having been formed in natural water channels. He did not believe, however, that such solution channels could have existed at the time of solidification of the igneous mass.

The paragenetic study of New Caledonian chromiferous rocks does not suggest that the chromite was injected into the already serpentinized rocks. The writer has found that the chromite grains are all highly fractured and show well defined mitred-structure. Cracks in the chromite are filled with either kämmererite or antigorite. The interlocking boundaries of chromite and olivine suggest contemporaneity of crystallization of these minerals. That the chromite was developed before serpentinization is indicated by the high degree of fracturing of the ore mineral and the filling of these fractures by serpentinous materials. Embayments in the chromite are commonly filled with kämmererite. This suggests that during the processes of serpentinization some solution of the chromite occurred. Kämmererite was thus formed instead of antigorite.

The occurrence of chromite in the joints of the serpentine, as outlined by Power, is not unlike the occurrences of the State-Line chromite deposits or those of the Bare Hills, Maryland,

[13] Power, F. D., "Mineral Resources of New Caledonia," *Am. Inst. Min. Engrs. Trans.*, 8, 1899–1900, pp. 439–442.

region. All these types may probably represent pipe-like injections of chromium-rich differentiates into an already solidified phase of the parent ultrabasic magma.

THE ORIGIN OF CHROMITE.

Criteria on Which Conclusions Are Based.

1. *Degree of Fracturing of Grains.*—Chromite of early magmatic crystallization is seldom fractured but grains in hydrothermally altered rocks may or may not be fractured. Lack of fracturing in the chromite grains may only be used as a criterion of chromite of later origin if other evidence of later crystallization is available.

2. *Chromite of Late Magmatic Stage.*—*a.* Occurrence in zones of granulation in comparatively fresh or slightly altered olivinic rocks, as in Alaska, Balsam Gap, N. C., and Selma, Oregon.

b. Disseminated grains of chromite in fractures of fresh or altered olivines, or in streaks cutting olivine, or in cleavages of enstatite (Fig. 9).

c. Elongated grains of chromite between individual minerals of the groundmass (Fig. 2 and 7).

d. Euhedral grains of chromite moulded on olivine crystals, as noted by Harker in his discussion of the rocks of Rum, and by the writer in some of the peridotites of Skye.

e. Anhedral grains of chromite, fractured or unfractured, showing apophyses into altered and unaltered minerals of the groundmass.

f. Accumulations of crystals, such occurrences having been termed "synneusis structure" (a together-swimming) by Vogt (Fig. 1).

Bowen is not in accord with Vogt's idea of the formation of such structures. He[14] discusses the development of chromite and picotite by crystal accumulation and believes that no high temperature is necessary. The process involves the formation of a spinel by reaction of olivine and basic plagioclase with a liquid of non-extreme (basic) composition. The spinel thus de-

[14] Bowen, N. L., *op. cit.*

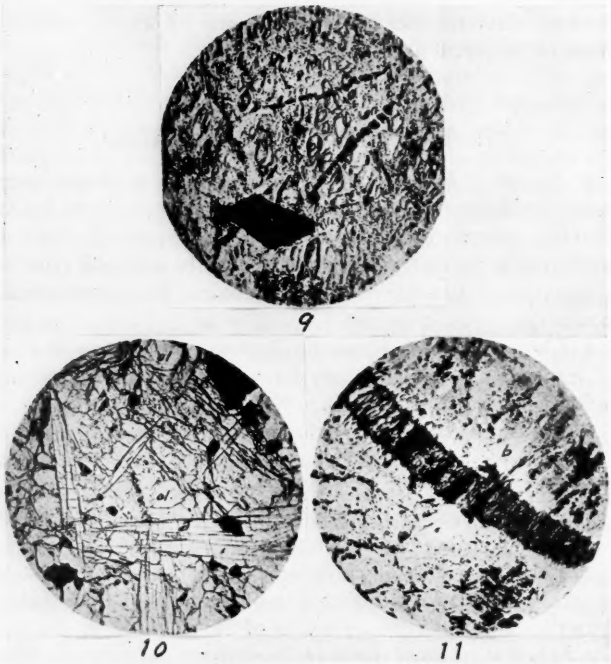

FIG. 9. Veinlet of late magmatic chromite traversing an olivine groundmass now partially antigoritized (*an*). From the Line Pit, State-Line Serpentine Belt. × 15

FIG. 10. Chromite of the hydrothermal stage associated with actinolite (*a*) occurring in a fairly fresh olivine groundmass. Chromite grain, upper left, is interstitial between olivine grains. In lower left, chromite cuts across olivine grain. North Carolina. × 15.

FIG. 11. Chromite of hydrothermal origin enclosed in a magnesite veinlet traversing a bastitized (*b*) groundmass. (From same slide as Figure 6). Jenkin's Pit, State Line Serpentine Belt. × 15.

veloped is a transient phase. Olivine is incapable of containing any considerable amount of chromic oxide and this oxide cannot enter in important amounts until a monoclinic pyroxene is developed. Crystal fractionation goes on and chromite and picotite may be developed locally. The excess material thrown out in the reactions described may be deposited in euhedral crystal accumulations as a sort of a pseudomorph after an earlier, resorbed mineral. Such accumulations are noted in the Rhodesian slides, and in the same slides hydrothermal chromite is developed in bastite.

3. *Chromite of the Hydrothermal Stage.*—Chromite of this stage is deposited along:

a. cleavages of the deuteric minerals as penninite, actinolite, talc and kämmererite (Fig. 10);

b. bastite zones (Fig. 6);

c. fibers of chrysotile veinlets; and

d. magnesite veinlets (Fig. 11).

e. Outlines of chromite are bordered by serpentine in entirely fresh rocks, as described from Dunsmuir, California.

4. The emplacement of the ore bodies is suggestive, in part, of chromite being introduced into the surrounding rock. Zavaritsky[15] has recently pointed out that the form and position of chromite grains indicates deposition in a mobile medium.

The types of occurrence of chromite deposits may be grouped under five general heads.

(*a*) Pipe-like or ore-shoot-like bodies.

(*b*) Sill-like bodies.

(*c*) Schlieren.

(*d*) Pockets or lenses.

(*e*) Placers (not considered in this discussion).

Pipe-like Bodies: These are well illustrated by the occurrences at the famous Wood Mine and the Line Pit deposits. In the latter case the pipe had a diameter of 6 to 8 feet and was completely sheathed by a zone of williamsite one foot in thickness. Antigorite is commonly associated with the chromite of Line Pit

[15] Zavaritsky, A. N., "Primary Platinum Deposits of the Urals," Russia. Comité Géol. Mat. pour la géol. gen. et appl., livr. 108, 1928.

and the chromite shows apophyses into the groundmass minerals. It is thus indicated that the chromite is probably of late magmatic origin. The gradation from a wehrlitic rock into a saxonitic type is sharp. The gradation from pure ore into williamsite is likewise abrupt. The ore body and the adjacent serpentine may represent basic differentiation products intruded into earlier formed peridotitic rocks toward the end of the magmatic period.

Sill-like Bodies: These are best illustrated by the occurrences in the Great Dyke of Southern Rhodesia and in the Bushveld Complex. In some cases, the serpentine borders of the chromite seams carry considerable ore mineral but rich zones seldom reach a width of more than four inches. The serpentine beyond the chromite vein is seldom enriched in chromite.

The current idea of formation regarding these African deposits is that they have been formed by gravitational differentiation. It would appear, however, that other processes must be involved to account for the layering.

Schlieren: This type of deposit is apparently not restricted to any one locality. One might assume that subsequent to the formation of a crystal mesh by fractionation, crystallization deformation movements, induced by earth pressures or by downward pressure of the overlying rocks or the magma itself, may result. Such movements would tend to "squirt" the interstitial liquor from the crystal mesh into regions of lesser pressure and form ill-defined streaks which are later in their period of formation than the enclosing rock.

Pockets and Lenses: The Bare Hills occurrence of chromite, the deposits of North Carolina and Norway are examples of this type of deposit. Only in the North Carolina localities are these deposits marginal. Lewis believed that convectional currents set up because of the temperature gradient between the cooler walls and the hotter portions of the magma would diffuse chromic oxide molecules toward the cooler walls. A lowering of the temperature would decrease the fluidity of the magma and such diffusion concentration would be insignificant. The writer believes that pockets or lenses of the ore might be formed by a process similar

to that believed to have been effective in the formation of synneusis or accumulative structures.

Previous Interpretations.

The earliest investigators, who attempted to unravel the history of chromite, believed that it was formed through the decomposition of chromium-bearing peridotites. Among those who supported such an idea were Arzruni,[16] von Groddeck,[17] de Launay[18] and others. Von Groddeck suggested that the formation of chromite deposits was contemporaneous with the serpentinization of the original rocks, dunites and peridotites. He believed that any iron liberated from the magnesian silicates would react with primary minerals carrying chromic oxide, such as chrome-diopside, picotite and others, to form chromite. Meunier[19] regarded the occurrences of native iron of Disco Island, of platinum and of chromite deposits, as formed by pneumatolytic processes wherein chlorides of platinum, nickel, iron and chromium played an important role. He believed that these processes followed closely after the intrusion of the magma. His views, were shared, in part, by de Launay.

Vogt[20] developed the idea of magmatic segregation as the only answer for the origin of chromite. He had then, and still has, an ample following in Pratt, Hall, Diller, Lewis, Humphrey and others. Rosenbuch was convinced, from a petrographic standpoint, that chromite, commonest in magnesia-rich rocks of the Archean, was like magnetite in that it belonged to the first generation of crystals. This early crystallization of chromite is indicated by the fact that it is usually enclosed by the next oldest

[16] Arzruni, A., Geol. d. Wiss. Christiania, 1873.

[17] Groddeck, A. von, "Die lehre von den lagerstätten der erze," Leipzig, 1879.

[18] Launay, L. de, "Gites mineraux et metalliferes," 1913, p. 257.

[19] Meunier, Stanislaus, "Contribution a l'histoire du fer chrome," C. R. 110, 1890, pp. 424–425; VII. Int. Geol. Cong. 1897, p. 157.

[20] Vogt, J. H. L., "Bildung von Erzlagerstätten durch Differentiationsprocesse in basischen Eruptivegesteinmagmata," *Zeit. f. prak. Geol.*, 1893, pp. 4–11; 125–143; 257–284. "Beitrage zur genetischen Classification der durch magmatische Differentiationsprocesse und Pneumatolyse entstanden Erzvorkommen." *Zeit. f. prak. Geol.*, 1894, pp. 384–393.

constituent, olivine. The greatest advance in the existing classification of ore deposits was made by Vogt in 1894 when he published his grouping of ore deposits:

I. Magmatic differentiation.
  a. Native metals.
  b. Oxidic Ores.
  c. Sulphidic Ores.
II. Pneumatolytic.

He included chromite under I-b on the basis of his study of the unaltered rocks of Hestmandø, Norway. He considered chromite to be the oldest mineral because of its euhedrism, and he stressed the point that in all cases the chromite appears to be the earliest consolidated constituent. In his co-operative work with Beyschlag and Krusch,[21] he says:

> The chromite deposits in peridotite show accordingly the same geological, petrographical and morphological characters as those of titaniferous iron in gabbro, and the general statements afterwards enumerated in connection with the titaniferous iron deposits hold good also for the occurrence of chromite.

Lindgren,[22] in accepting Vogt's idea in regard to many ore bodies, expressed the opinion that chromite might be secondary in some cases and formed from picotite, chrome-diopside or primary chromite during the processes of serpentinization.

The statements of Vogt had little effect on Power [23] who, after a study of the New Caledonian mineral resources, held to the idea that chromite represented material formed during the natural process of oxidation accompanying the hydration and weathering of the original ultrabasic rocks.

Hall and Humphrey [24] regard the chromite deposits of the

[21] Beyschlag, F., Krusch, P., and Vogt, J. H. L., "The Deposits of the Useful Minerals and Rocks," . . . tr. by S. J. Truscott, 1914, p. 246.

[22] Lindgren, Waldemar, "Mineral Deposits," N. Y., 1913, p. 747.

[23] Power, *op. cit.*

[24] Hall, A. L., and Humphrey, W. A., "On the Occurrence of Chromite Deposits along the Southern and Eastern Margins of the Bushveld Plutonic Complex," *Geol. Soc. South Africa, Trans.*, 11, 1908, pp. 69–77.

Transvaal as local segregations or concentrations of grains brought about by differentiation of the magma of the Bushveld Complex. They point out that chromite shows perfect crystal outlines and these encroach on other minerals. The next endorsement of the theory of magmatic segregation of chromite was by Cirkel,[25] who said:

> . . . the actual formation of chromite must have been effected during the cooling or solidification of the magma under conditions which cannot be sufficiently explained.

The foregoing ideas represent those who have supported or opposed the magmatic segregation theory of the formation of chromite.

In 1916 it was suggested by Tolman and Rogers,[26] following an exhaustive study of sulphide ores, that in many cases the ore minerals were introduced subsequent to the crystallization of the primary silicates. In fact, the introduction of such ores marked the third step in the orderly series of events recognized by these writers. Their sequence is:

a. Crystallization of primary silicates;

b. Development of hornblende and biotite, and occasionally tourmaline, garnet, as magmatic alteration products;

c. Introduction of ore minerals;

d. A small amount of rearrangement of the ores and the development of secondary silicates by hydrothermal waters.

They question the interpretation that Vogt gives for his figures, and state: "Examination of his figures shows irregular as well as subhedral forms; and the alternate hypothesis that chromite octahedra are formed at a late stage is worthy of consideration."

The present writer raises the same question regarding Diller's interpretation of the forms of chromite in the Dunsmuir, California, slides and on his sequence of crystallization of the ore- and the groundmass-minerals.

[25] Cirkel, Fritz, "Report on the chrome iron deposits in the eastern townships, province of Quebec." Can. Dept. Mines. Mines Branch. Ottawa, 1909.

[26] Tolman, C. F., and Rogers, A. F., "A Study of Magmatic Sulfid Ores," Leland Stanford Jr. Univ. Publ. 1916. Summary T. No. 1.

Singewald,[27] commenting on the work of Tolman and Rogers, stressed the point that the French school, ably headed by de Launay, had always recognized the role of mineralizers in the formation of ore deposits, and that though accessory ore minerals may precede rock minerals, even in the so-called magmatic segregations the ore minerals are later than the rock-forming minerals. Thus the French school recognizes no gap in the mineralization between the freezing of the original molten magma and the deposits formed through the extraction of material from the magma by mineralizers. Singewald was of the opinion that a paragenetic study of the chrome ores would show that the chromite was not an early magmatic mineral but that it also formed mainly later than the non-metallic minerals of the igneous rock. The present writer has found that many of the low grade Rhodesian ore specimens show chromite occurring interstitially between groundmass minerals (Fig. 7).

The ideas of origin of the chromite deposits of Oregon advanced by Westgate [28] and those that Gordon [29] has promulgated for the State-Line serpentines are essentially the same. The general plug-like shape of the chrome-ore body of the Line Pit (State-Line Serpentine Belt) is suggestive of a later period of formation than the surrounding rock. The present writer's study of thin sections from this pit strengthens this idea. Euhedral forms of chromite are almost lacking and the outlines of the grains, irregular and feathery, show apophyses into the groundmass minerals. This indicates that chromite crystallization was either contemporaneous with, or later than, the formation of the groundmass minerals of the plug.

Westgate suggests that, in the case of the Oregon deposits, differentiation took place at a good distance below the present land surface, and chromite deposits and peridotite resulted from the split-off of the general magma, but not from the same stock that

[27] Singewald, J. T., Jr., "Magmatic Segregation and Ore Genesis," *Min. and Sci. Press*, 114, 1917, pp. 733–736.

[28] Westgate, L. C., *op. cit.*

[29] Gordon, S. G., "Chromite Deposits of the State-Line Serpentines," *Acad. Nat. Sci. Phila. Proc.*, 73, 1921, pp. 449–454.

is represented by the pyroxenite. He believed that differentiation in place was a subordinate factor in the formation of the ore.

Conclusions Based on Present Study.

The following sequence of crystallization is recognized in the chromiferous rocks.

1. Crystallization of early magmatic chromite is well advanced before the initial crystallization of the groundmass minerals. Final freezing of early magmatic chromite overlaps the formation of the groundmass silicates.

2. Crystallization of late magmatic chromite which replaces, either partially or completely, the groundmass minerals, and surrounds, embays, or cuts these minerals, or penetrates the cleavable minerals. *Chromite formed during this period in greater quantity than during the other periods.*

3. Chromite of the hydrothermal period, which is more important in some deposits than in others, is distinctly later than the magmatic period and is associated with two distinct groups of minerals: (*a*) Early hydrothermal minerals—Anthophyllite, actinolite, and tremolite; (*b*) Late hydrothermal minerals—Chlorite, talc, kämmererite, penninite, serpentine and magnesite.

Chromite of this period was probably derived by the hydrothermal solutions from the parent rock or from other rocks which they traversed. The rounded outlines of the chromite of the early, and possibly the late, magmatic stage are suggestive of corrosive action by hydrothermal solutions. The chromium thus obtained has been deposited in bastite zones, chrysotile fibers, in magnesite, between kämmererite or penninite plates, and in the cleavages of the early hydrothermal minerals.

It is difficult to determine accurately the amount of chromite deposited along cleavages or interstitially between plates of deutric minerals by hydrothermal solutions. In Fig. 6, chromite occurs with its longest dimension parallel to the direction of the bastite zones, and apophyses of chromite project into the bastite. Such chromite might have been deposited also as a product of late mag-

matic origin along the cleavages of the original silicates (enstatite in the example noted) before their alteration to serpentine.

The largest deposits of chromite are in serpentinized rocks, and this suggests that the concentration of the ore mineral is proportional to the amount of serpentinization that the original chromiferous rock has undergone. This implies that the hydrothermal solutions, which produced the serpentinization, carried and deposited the chromite. The only apparent sources of such chromium is either in the reworking of earlier formed chromite or in waters of meteoric origin.

Some authorities believe that an ultrabasic magma is incapable of supplying enough water to produce serpentinization but believe that the necessary waters may be derived from the complementary acid phases of a cooling basic mass. The State Line serpentines, which show excellent examples of hydrothermal chromite, are cut by albitite dikes that are not deformed and are later than serpentinization. This process of alteration is a later hydrothermal one and is probably produced by greater concentration of solutions from sources that were deeper in the cooling mass than those that produced the earlier hydrothermal minerals, actinolite, tremolite and anthophyllite. The exact position of serpentinization in the series of events beginning with the crystallization of the magma and ending with the latest hydrothermal action is not known.

4. A study of the chemical composition of chromite from different localities indicates that there is no apparent correlation between:

a. the composition of chromite and its mode of occurrence;

b. the composition and sequence of crystallization of the chromite and the groundmass minerals; and,

c. the composition of chromite and the degree of alteration of the chromiferous rock.

It is further indicated that the mineral called chromite cannot be expressed by a definite chemical formula.[30]

[30] Fisher, L. W., "Chromite: Its Mineral and Chemical Composition." (In press—*Amer. Min.*)

SUMMARY.

The notion that chromite deposits have originated through primary crystallization *in situ* has been greatly overemphasized. Chromite of the late magmatic period is of much greater importance than that of the early magmatic period. Hydrothermal solutions causing serpentinization have played an important role in the formation of chromite deposits by dissolving magmatic chromite and redepositing it with the hydrothermal silicates.

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A DIABASE CONTACT–METAMORPHIC MINERAL DEPOSIT IN ONTARIO.[1]

FRELEIGH FITZ OSBORNE.

DURING the course of areal geological mapping for the Ontario Department of Mines the writer examined a mineral deposit formed by the replacement of limestone adjacent to an intrusion of diabase. The limestone is silicated, and a rather unusual number of metallic minerals are present. Other mineral occurrences in the vicinity show relationships suggesting the nature of the solutions that produced the silication and formed the ore. It is the purpose of the present paper to describe the deposit and to present evidence bearing on the nature of the solutions that formed it.

The occurrence is on a property known as the Iron Mask Cobalt Silver Mines. It is in the northern part of Hart Township, Sudbury District, Ontario, about five miles by trail from Cartier, a divisional point on the Canadian Pacific Railway forty miles west of Sudbury.

ROCK FORMATIONS.

The following table summarizes the rock formations of the area.

Post-Huronian	Keweenawan (?)	Basic Intrusives. *Intrusive contact*
Huronian	Cobalt Series	Lorrain Formation Gowganda Formation *Disconformity*
	Bruce Series	Serpent Formation Espanola Formation Mississagi Formation *Non-conformity*
Pre-Huronian	Algoman (?)	Granite *Intrusive contact*
	Keewatin (?)	Gneisses and Schists

[1] Published with the permission of Thos. W. Gibson, Esq., Deputy Minister of Mines for Ontario.

The pre-Huronian formations consist of gneissic, schistose, and granitic rocks. The gneisses and schists, which are rather basic, are characterized by hornblende and a steeply dipping foliation. They were intruded and greatly altered by the granitic rocks. Most of the ore deposits in the district were formed in pre-Huronian time as the result of the intrusion. The mineralization described here is of much later age and not connected with granitic rocks.

The Bruce series overlies the pre-Huronian rocks non-conformably. Its basal formation is the Mississagi, consisting of arkose with some conglomeratic members. It grades upward into the Espanola formation, which consists of thinly bedded impure limestone ranging from 25 to 125 feet thick. The Espanola formation grades into the overlying Serpent formation. The base of the formation is composed of fine clastic rocks, but they grade upward into conglomerates. The Serpent formation is separated from the overlying formation of the Cobalt series by a disconformity.

Diabase dikes and sills intrude all the formations described above. In the pre-Huronian and the more massive parts of the Huronian rocks, dikes are numerous; however, in the well-bedded parts of the Huronian, sills preponderate. The intrusives of this age range in thickness from a few inches to over 500 feet. Near the ore deposit a thick diabase body cuts the Huronian series just below the base of the Espanola formation. The body is sill-like in that it conforms to the dip of the overlying rocks, but a short distance to the east, it appears to be above the Espanola formation. A heavy mantle of drift prevented determining whether this position is due to cross-cutting or to assimilation of the limestone by the magma of the diabase.

The writer took only a few specimens of the intrusive rock, and they show that the rock mass is more properly an amphibolite than a diabase. It is believed that the original quartz diabase was altered by its own volatile constituents. The mode of occurrence and microscopic features all confirm the relationship of the altered rock to normal quartz diabase of this area and other parts of

Ontario. In hand specimens, this rock is of a general dark green color with glistening ferromagnesian constituents and dull feldspathic grains. It resembles much of the more massive pre-Huronian gneiss; in places it is only the presence of the foliation which serves to distinguish them. The diabase-amphibolite shows a tendency toward a linear arrangement of the constituents parallel to the contact. In places bands of coarser grain are found within the rock. Some of these bands contain ferromagnesian minerals up to three centimeters in length.

Petrography of the Diabase-Amphibolite.—The rock is medium to coarse grained with a tendency toward an ophitic texture. All pyroxene is gone, and amphibole is the femic mineral. At least two varieties are present; one, with pleochroic tints in green and yellow, is hornblende. Variation in pleochroic colors suggests a range in chemical composition. Another amphibole occurs as a fringe around the hornblende where it is in contact with interstitial feldspar and quartz. It is rather fine in grain and forms sheaves and radiating groups which appear to replace the granophyric intergrowth and quartz. It has a low extinction angle and is pleochroic in yellowish green and blue. It is apparently near the abnormal glaucophane of Winchell.[2] The aggregate is too fine for a more precise determination. Glaucophane has been described as a reaction product in a diorite by Denaeyer.[3]

The feldspar, which is slightly altered to white mica and epidote, shows a uniform zoning from calcic andesine at the core, outward to oligoclase. At the margins it is intergrown with quartz giving a poorly-defined granophyric texture. A more intricate intergrowth of feldspar and quartz is found interstitially to the plagioclase and amphibole, and not in optical continuity with the plagioclase. The feldspar of this intergrowth is much clouded with alteration products, and by analogy with the intergrowths described by Shannon[4] is probably the potassic variety.

[2] Winchell, A. N., "Elements of Optical Mineralogy," Pt. II., p. 209, 1927.

[3] Mügge, O., "Mikroskopische Physiographie der petrographischen wichtigen Mineralien," p. 539, 1927; Denaeyer, M. E., "Les Roches de l'Adrar des Iforass et de l'Ahaygar," *Compt. Rend.*, 176, p. 1161, 1923.

[4] Shannon, E. V., "The Mineralogy and Petrology of Intrusive Triassic Diabase at Goose Creek, Loudoun County, Virginia," *U. S. Nat. Mus. Proc.*, 66, pp. 1–86, 1924.

Some quartz without intergrowth is found interstitially. Both quartz and granophyre are cut by apatite needles.

The writer believes that the rock was originally a quartz diabase but the alteration due to end-stage products of crystallization, removed all trace of pyroxene and formed the amphibole. At a still later stage the rest-solution became enriched in alkali metals and silica and the granophyre and glaucophane were formed. The naming of the rock presents some difficulty: its present mineralogical composition merits the name amphibolite; however, amphibolites are known to be formed in several ways,[5] so the name does not indicate the igneous origin of the rock. The writer will refer to it in the rest of this paper as a diabase.

Espanola Formation.—The unmetamorphosed Espanola formation in this area is a slightly-magnesian limestone that contains much clay. Under the microscope some sections show ten bands of clay per millimeter. In other places clayey bands about one centimeter thick are separated by relatively pure limestone. The limestone has a few angular grains of quartz and unoriented leaves of muscovite, set in a matrix of finely crystalline carbonate.

CONTACT METAMORPHISM OF THE LIMESTONE.

The contact-metamorphism produces marked changes in the rock: it becomes coarsely crystalline and new minerals are grouped parallel to the bedding planes. It is notable that the new minerals in these groups are not those that might be expected to form from impurities, but include such minerals as quartz. From this it is clear that texture of the rock more than the impurities governed the distribution of the new minerals. The following minerals were noted: garnet, diopside, quartz, biotite, wollastonite, and a ferriferous chlorite. No regular zoning of the non-metallic minerals could be determined, although garnet and wollastonite do show some tendency to be closer to the contact with the diabase.

Some of the marble formed by the recrystallization of the limestone contains much biaxial calcite. In part the formation is altered to an aggregate of garnets containing many quartz inclu-

[5] Adams, F. D., and Barlow, A. E., "The Geology of the Haliburton-Bancroft Area, Ontario," Geol. Surv. Canada, Mem. 6, p. 161, 1910.

sions and showing interstitial calcite. The garnets are of a pale yellow color and show a feeble birefringence. Some of them show a sector structure resembling that of cordierite, and others, a network of birefracting garnet contained within isotropic garnet. In some places the garnet diminishes in amount, and radiating groups of wollastonite surround and appear to replace it. The wollastonite is in rather fine needles and with the garnet makes up practically the whole rock.

A part of the rock consists of coarse calcite and an aggregate of diopside arranged parallel to the original bedding. This aggregate is rather fine and it is not certain that it does not have intermixed wollastonite. In some places the only change is the formation of marble and the introduction of quartz parallel to the bedding planes. Many of the quartz grains show uncorroded outlines. In one place a large mass of limestone has been replaced by a network of quartz crystals about one centimeter in diameter. A small amount of biotite appears in the contact zone. It replaces the carbonate and shows some haloes. Another mineral which appears to replace part of the marble is chlorite. It is a strongly colored green variety.

Metallic Minerals.—The megascopically visible minerals are magnetite, pyrite, chalcopyrite, galena, sphalerite, and a cobalt mineral. Unlike the non-metallic minerals these show a tendency toward a zoning, so much so that all cannot be found in one specimen. A body of impure magnetite is exposed for about 400 feet and is found as sporadic outcrops for about the same distance in the limestone next the diabase. At one time this property was exploited as a source of iron ore. Chalcopyrite and pyrite replace the coarsely crystalline marble and contact silicates at a greater distance from the contact. The pyrite is euhedral, but the chalcopyrite is interstitial to the silicate and carbonate minerals. A sphalerite-galena zone is outside the pyrite-chalcopyrite zone and exhibits two modes of mineral occurrence. In one, the minerals are irregular and parallel to the bedding planes; in the other they occur as veins associated with quartz. In the irregular masses the gangue mineral is garnet. The mineralization by cobalt seems to

be still farther from the diabase-limestone contact. It is found with the network of quartz crystals replacing the limestone. The space between it and the pyrite-chalcopyrite zone is not exposed, therefore it is necessary to infer that the galena-sphalerite zone, which is very discontinuous, may separate them.

The hypogene cobalt mineral gives blowpipe tests for Co, Fe, As, and S. Its mineralogy will be discussed later in this paper. The network of quartz crystals with which it is associated is stained with erythrite. Mr. C. H. Rickaby, who has examined the property for the Ontario Department of Mines, took a specimen and assayed it. It contained no silver and 80 cts. in gold per ton. This is in harmony with the generalization [6] that gold occurs with cobalt minerals where quartz is present, and silver where it is absent.

SPECULARITE IN OTHER DEPOSITS RELATED TO DIABASE.

Specularite is found in the non-calcareous parts of the Bruce series near diabase masses. This is true particularly to the east of the deposit being described, and it is related to the same diabase body. In these rocks the specularite is found with quartz, and magnetite is absent. In some of these, small veins of sphalerite and galena have been found, but as yet no commercial body has been discovered in non-calcareous rocks of Huronian age in this area. In the calcareous parts of the formation specularite is not found, but magnetite is. It seems reasonable that the emanations from the diabase were of uniform character but that the presence of the limestone caused magnetite rather than specularite to form.

Mineralography.—A number of polished sections of the iron oxides were examined. Some were from the deposits in or near limestone and others from non-calcareous rocks. Much of the magnetite shows the usual equidimensional grains; some, however, replaces calcite as thin laminae. Parts of these laminae etch with varying rapidity with concentrated HCl and they are seen to con-

[6] Uglow, W. L., and Osborne, F. F., "A Gold-cobaltite-lodestone Deposit, British Columbia, with Notes on the Occurrence of Cobaltite," ECON. GEOL., vol. 21, pp. 285–293, 1926.

sist of magnetite grains in varying orientation. The form of the magnetite suggests its original deposition as specularite and its subsequent reduction to magnetite. The specularite with quartz in the non-carbonate rocks does not show a trace of magnetite even after prolonged etching [7] with HCl.

The mineralographic investigation showed nothing unusual about the pyrite, chalcopyrite, sphalerite, and galena. The fact that the deposit is zoned prevents a determination of the paragenesis.

The identity of the cobalt mineral is in doubt.[7a] The material is microscopically homogeneous. It is slightly attacked by long etching with nitric acid, but is negative toward HCl, KCN, $FeCl_3$, $HgCl_2$, and KOH. These are the reactions for glaucodot,[8] and the blowpipe determination is in agreement. However, glaucodot is orthorhombic, and this mineral is not appreciably anisotropic with polarized reflected light. It is possibly an isometric analogue of glaucodot and therefore a ferriferous cobaltite.

[7] Osborne, F. F., "Technique of the Investigation of Iron Ores," ECON. GEOL., vol. 23, pp. 443–450, 1928.

[7a] Since this paper was written an analysis of the cobalt mineral described here has been made by Mr. J. G. Fairchild in the laboratory of the United States Geological Survey. The sample submitted was a part of a polished surface and therefore contaminated with rouge. Some gangue is also present.

	Per cent.	Ratio
Co	20.08	340
Ni	6.35	108
Fe	5.82	104
As	36.20	483
S	15.47	483
CaO	4.65	
MgO	2.35	
CO_2	6.23	
Insol	3.84	
	100.99	

The analysis confirms the relationship of the mineral to the cobaltite group.

[8] Davy, W. M., and Farnham, C. W., "Microscopic Examination of the Ore Minerals," p. 91, 1920.

ORE FORMATION.

The occurrence of the granophyric intergrowths and glaucophane indicate that the end-stage product of crystallization of the diabase magma was enriched in alkali metals and silicon. The introduction of soda and silica from a diabase in the formation of many hornfels and adinoles has been proved in many places.[9] The presence of apatite also indicates a concentration of volatile constituents. It seems probable that the contact metamorphism of the limestone was produced by the escape of these end-stage products, and that they introduced the metallic minerals. No sodium or potassium mineral may be recognized in the contact zone; however, a great deal of silica was introduced. It is possible that some magnesium was brought in to form the diopside, but this cannot be proved because of a possible original content of magnesium in the limestone. In the localities described in the paper cited above, considerable magnesium was introduced from the diabase, and cordierite was formed.

Wollastonite, which is in the contact zone, has been synthesized in various ways, with and without fluxes. A method devised by Gorgeu[10] is instructive in considering this occurrence. He obtained it by the action of calcium chloride on silicic acid in the presence of water. It is probable that all these compounds were present in the contact zone at the time of the formation, and it may have been formed in that manner.

The manner of formation of the iron ore minerals is of especial interest in the consideration of the genesis of the deposits because iron exists in two states of oxidation. It has been suggested that the iron-ore minerals were formed from emanations,[11] in which the iron was in the ferrous state. It is possible that the iron was introduced in the ferric state, either as the fluoride or chloride. Ferric chloride is easily volatile. Its boiling point is given as

[9] Milch, L., "Ueber einige Diabaskontaktgesteine," *Neues Jahrb.*, Beil. Bd. LVII., 841–894, 1928. Contains a number of references.

[10] Mugge, O., *op. cit.*, p. 452.

[11] Leith, C. K., and Harder, E. C., "The Iron Ores of the Iron Springs District, Southern Utah," U. S. Geol. Surv. Bull. 338, 1908; Butler, B. S., "A Suggested Explanation of the High Ferric Oxide Content of Limestone Contact Zones," ECON. GEOL., vol. 18, pp. 398–404, 1923.

315° C.[12] The corresponding ferrous salt boils at about 850°–900°.[13] For this reason it seems probable that the ferric salts are more likely to be present in the emanations than the less volatile ferrous compound. The iron may be precipitated as hematite in the non-carbonate rocks; it may be deposited as magnetite by the reduction of the ferric compounds in the presence of limestone; or specularite may be reduced to magnetite after deposition. A reduction of a ferric compound to form magnetite was suggested by the writer[14] in 1925 as a result of the study of some magnetite deposits. The conclusion was not published at the time, but the further evidence afforded by the deposits in the area being described and the work by Stirnemann lend it support.

The formation of hematite by the interaction of ferric chloride and water at moderate temperatures has been investigated by Sternemann.[15] This is probably the reaction that took place in the non-calcareous part of the Huronian, where specularite is found with quartz alone.

The occurrence of the reduced oxide, magnetite, in deposits in or near limestone points to reduction of ferric compounds by the action of the limestone. Two cases are possible: the solution may be reduced at the time of deposition so that magnetite is formed, or specularite is reduced to magnetite after deposition. The unoriented magnetite grains making up the lamellae are probably pseudomorphs after specularite and therefore caused by reduction after deposition. Pseudomorphs of magnetite after specularite have been described from a number of localities. One of the most recent descriptions is by Smitheringale.[16] He describes the reduction of magnetite to hematite in the ore from the George Gold-Copper Mine, Portland Canal. In the same district the writer

[12] Van Nostrand's Chemical Annual, p. 218, 1926.

[13] Stirnemann, E., "Ueber die Bildungsverhältnisse der Eisenerlagerstätten im System Eisenchlorid-Wasser," Neues Jahrb. Beil. Bd. 53, p. 60, 1926.

[14] Osborne, F. F., "The Magnetite Occurrences of the West Coast of Vancouver Island, B. C.; their Contact Metamorphism and Ore Genesis," University of British Columbia, unpublished essay, 1925.

[15] Stirnemann, E., *op. cit.*

[16] Smitheringale, W. V., "Mineral Associations at the George Gold-Copper Mine, Stewart, B. C.," ECON. GEOL., vol. 22, p. 204, 1928.

has seen many quartz-specularite veins, which very much resemble those described in this paper. Intercalated limestone bands in the Bear River formation, in which the deposit occurs, may be responsible for the reduction. Smitheringale also mentions the occurrence of magnetite in the same relation in the Cornwall District, Penn.[17] The type of country rock in this locality is very similar to that described in this paper.

The geological evidence in the area described points to a reduction of the ferric compounds in the presence of $CaCO_3$; the actual reducing agent may be CO, and the following reaction may be written

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2.$$

Matsubara[18] has shown that this reaction is practically irreversible at atmospheric pressure, and that the reaction goes on readily at 863°. A curve published by Butler[19] shows that above 500° a decreasing concentration of CO is necessary to reduce ferric oxide. Hesemann[20] has suggested the reduction of ferric to ferrous salts by the action of carbonaceous material in certain Devonian iron ores. He believed that emanations from rocks of various basicities formed hematite by interaction with sea water but some was reduced to magnetite by the action of CO.

Winchell[21] has suggested one method by which CO may be developed in the contact zone. He shows that at Bingham there has been an elimination of carbon near the intrusive, and suggests that it is due to the following reaction

$$C + CO_2 = 2CO.$$

[17] Spencer, A. C., "Magnetite Deposits of the Cornwall Type in Pennsylvania," U. S. Geol. Surv. Bull. 359, 1908.

[18] Matsubara, A., "Chemical Equilibrium between Iron, Carbon, and Oxygen," Trans. Am. Inst. Min. Eng., 62, p. 8, 1922.

[19] Butler, *op. cit.*, Fig. 65. From Findlay, "The Phase Rule and Its Applications," p. 308.

[20] Hesemann, J., "Die devonischen Eisenerze des Mittelharzes," *Abh. zur prakt. Geol. und Bergw.*, Bd. 10, p. 33, 1927.

[21] Winchell, A. N., "Petrographic Studies of the Limestone Alteration at Bingham," *Trans. Am. Inst. Min. Eng.*, 70, p. 896, 1924.

This reaction is slow at 600 degrees and atmospheric pressure, but is rapid at 800 degrees. A volume change accompanies the reaction so that a higher temperature would be required at increased pressure. However, since the reduction of ferric oxide is practically irreversible, only a small concentration of CO would be necessary.

CONCLUSIONS.

The quartz diabase magma intruded the Huronian rocks as a sill. As it consolidated, volatile constituents altered it to an amphibolite. The emanations escaped from it and altered the country rock, by forming contact metamorphic silicates. The material introduced was characterized by the presence of ferric salts, which were reduced to magnetite at the time of deposition or later by the action of limestone. The rapidity of cooling or the thinness of the favorable Espanola formation overlying the diabase caused the deposit to be unusually "telescoped." The whole series of zones, magnetite, pyrite-chalcopyrite, galena-sphalerite, and cobalt are compressed within the stratigraphic thickness of the formation, 125 feet. Each zone of the deposit shows characteristics which link it with deposits associated with rock of a similar basicity. The magnetite mineralization is similar to that of the Cornwall District, Penn.,[22] and Iron Springs, Utah.[23] The pyrite-chalcopyrite and the sphalerite-galena zones show features in common with a series of Siberian deposits described by Weigel.[24] The similarity of the cobalt zone to the deposits of Cobalt Ontario, is striking.

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[22] Spencer, A. C., *op. cit.*

[23] Leith, C. K., and Harder, E. C., *op. cit.*

[24] Weigel, O., "Über einiger Erzlagerstätten am Sichotin-Alin in Ostsiberien," *Neues Jahrb.*, Beil. Bd. 37, pp. 653–736, 1914.

THE GRAPHITE DEPOSITS OF LOUISA, QUEBEC.

GEO. W. BAIN.

INTRODUCTION.

Location.—The graphite deposits described in the following pages lie in the southern part of Wentworth Township in Argenteuil County, Quebec. The nearest railroad station is on the Canadian Pacific Railway forty miles due west of Montreal at Lachute ten miles south of the deposits (Fig. 1). The area lies

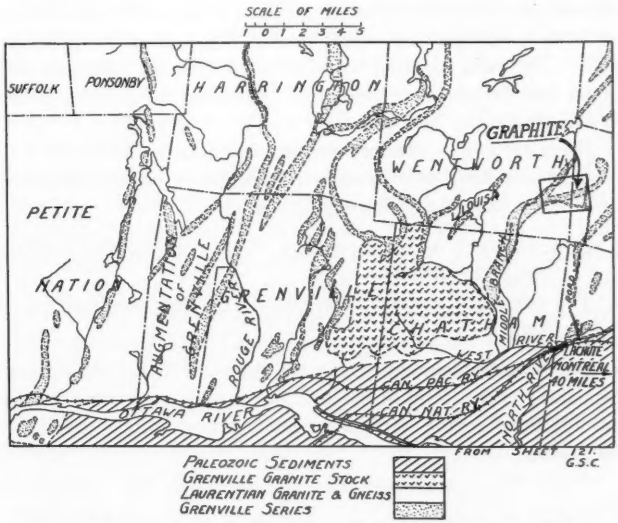

FIG. 1. Map showing location and general geological setting of the Louisa graphite deposits.

on the borderland between the rugged hill country around the edge of the Laurentian Shield and the flat peneplain upland of the shield proper.

Historical Sketch.—For over thirty years small quantities of graphite had been known to occur at a number of places in the southern part of Wentworth township, Quebec. An attempt was made to work a deposit near Boyd Lake and the almost pure mineral recovered from the veins in a primitive fashion. Exploration of the land east of Boyd Lake by diamond drilling and drifting was undertaken in recent years but was carried on without any regard to geological structure controlling the occurrence of the graphite deposits and was totally unsuccessful.

Subsequent exploration in 1924 farther to the east uncovered a rich vein of graphite which was said to be four to six feet wide and almost pure. Preliminary examination of this deposit showed that it carried about 15 per cent. of graphite over a width of from 3 to 5 feet and single masses a foot thick were obtainable. The vein appeared to be either a silicated limestone bed, or an unusual pyroxene pegmatite following the bedding planes of the graywacke wallrock.

The Problems.—The preliminary examination indicated that the vein was sufficiently promising to deserve more detailed study in order to settle the following problems:

1. Structural control of deposition of the mineral and localization of the deposits.
2. The origin of the graphite and its possible continuation in depth.

Ten days were spent examining the deposit and the older workings and trenches, and in preparing a detailed geological map of the adjoining region, to supplement a regional study previously completed.

SUMMARY AND CONCLUSIONS.

General Features.—The graphite occurs as disseminated flakes, in veins, in pegmatites, and as replacement deposits in the Grenville Series, divisible at this locality into an upper shaly graywacke member separated from a lower crystalline limestone member by a quartzite ranging from almost nothing to twenty feet in thickness. All deposits are located near the contact between

the limestone and the graywacke and are on the flanks or crest of minor crumples on the major anticline which brings the crystalline limestone to the surface along the Boyd Lake trough. The axial planes of the folds plunge south and all known deposits have been found to the south of a limestone outcrop, that is on the hanging side of the asymmetric folds. Laurentian granite and associated pegmatites intrude the sediments.

The Graphite Deposits.—The graphite occurs in two principal types of deposits:

1. In columnar form in pegmatite dikes.
2. In flake and massive form in hydrothermally altered skarn.

The graphite of the pegmatite dike deposits occurs in association with, and as a part of, veinlets of sericitized albite and quartz, both cutting and replacing unchanged orthoclase pegmatites. This graphite has either a columnar or a radiating structure and in instances makes up most of the secondary pegmatite.

The graphite of the skarn occurs in places where the pyroxene has been highly uralitized and the uralite changed locally to chlorite. The introduction of the graphite is plainly independent of, and later than, the silication of the limestone from which the skarn was made and was brought about by solutions of silici-alkalic type which are usually responsible for uralitization and chloritization. Only hydrothermally altered skarns contain more than scattered flakes of graphite and not all these bear noticeable quantities of it. The graphite is flaky, massive or radiating but never columnar.

Origin.—The graphite was introduced by solutions which caused sericitization of albite, but not of the orthoclase of the pegmatites, and which changed the pyroxene of the skarns to uralite and chlorite. Such solutions are regarded as being silici-alkalic in composition and pegmatitic in origin.

GENERAL GEOLOGY.

The geological members and sequence of events recorded in this area may be summarized in tabular form as below.

Pleistocene	Glacio-fluvial deposits
?	Porphyritic olivine diabase
Laurentian	Pegmatite and aplite Granite (at least two intrusions) Femic dikes
Grenville Series	Graywacke Quartzite Limestone Quartzose graywacke (intruded out in vicinity of deposits).

Grenville Series.

The Grenville Series is separated into a lower limestone and an upper thinly bedded graywacke by a quartzite of variable thickness. No gradation of the limestone into the quartzite was observed so that the contact surface may represent a disconformity or a minor unconformity.

Grenville Limestone.—The limestone is composed for the most part of loosely interlocked calcite grains one eighth of an inch or more in diameter; the rock is white or blue, and the crystals transparent or very translucent. Dolomitic beds are more massive, finer, grained, and have an earthy lustre. Dark bands or zones rich in sparsely disseminated graphite indicate former bedding. Siliceous beds from a quarter of an inch to three inches thick frequently parallel the graphitic streaks. Folding has broken the siliceous layers and separated individual pieces by limestone which flowed into the cracks. The length of a bed is often doubled by deformation in this fashion and at the same time the thickness of adjacent beds thinned by a corresponding amount.

Recrystallization of impurities and addition of materials by emanations from the subjacent batholith has resulted in the formation of several minerals foreign to the original limestone series, sometimes in such abundance as to make up a large portion or all of the rock. The limestone beds are most susceptible and carry a greater abundance of these introduced and recrystallized minerals than the dolomite beds or siliceous layers. Among the

more numerous introduced minerals are anorthoclase, brown vesuvianite, diopside, apatite, and titanite.

Anorthoclase resembles the calcite of the limestone in texture, shape and structural arrangement, and seems to be a metasomatic replacement of the earlier carbonate with complete preservation of its form; large irregular granular bunches are common so that although simple pegmatitic injection is not noticed the more intimate soaking and replacement by pegmatitic solutions migrating irregularly through the rock has given a massive structure not generally recognized as a result of pegmatitic injection. No graphite has been found in silicated limestone of this type.

Tetragonal prisms of brown vesuvianite and wedges of titanite are scattered through the silicated zones. These crystals usually have good outlines but often contain embayments of calcite and feldspar which they replace. Diopside and apatite in green grains or prisms are sparsely disseminated through the rock but become more abundant in certain contact zones where they are the predominating minerals. Graphite, in rare glistening flakes, coats crystals or occurs within them where the above silicates predominate over anorthoclase. Whether or not the graphite is an introduced mineral is difficult to determine but the fact that it is more abundant along and parallel to bedding planes might seem to indicate that it was formed from carbonaceous and bituminous matter originally present in the rock. On the other hand the comparative rarity of graphite in or along the siliceous zones, which in unmetamorphosed limestones carry most of the carbonaceous or bituminous matter, might indicate that the graphite was a mineral introduced along the more porous zones contemporaneous with the vesuvianite, alkali feldspar, or diopside, or a mineral formed by the reduction of CO_2 freed during the silication of carbonates by pegmatitic solutions following these porous zones. As yet the primary or secondary nature of the carbon associated with and sparsely disseminated through silicates can scarcely be settled satisfactorily, even although the importance of igneous agencies in giving the mineral its present position is fully recognized.

Quartzite.—The noses of plunging anticlines of limestone pass beneath the quartzite so that there can be no doubt but that the quartzite is the younger of the two rocks. No gradation from one rock to the other was recognized even where only ten feet of drift intervened between the outcrops of the two strongly contrasted types. The quartzite is extremely white and almost massive, nearly all traces of stratification having been destroyed by recrystallization. In many places the member resembles the injected quartz pegmatites found in the graywackes but close examination of the outcrop reveals ghosts of the former bedding planes.

Just east of Number 1 lode, the member is 20 feet thick and at the Number 6 vein it is only a few inches wide. The chief significance of the member is as a horizon marker and as a means of distinguishing the sharp upper contact of the limestone from the lower gradational contact so admirably exposed on Lake Louisa 4 miles to the west.

Graywackes.—The major portion of the area of sediments is underlain by dark, rusty weathering graywackes. As a rule the only evidence of bedding is the presence of schistose biotite bands in between more massive beds. In other cases color differences between adjacent beds is sufficiently distinct to identify them. More rarely thin quartzite beds, separated by recrystallized shaly layers, confirm the position of bedding identified upon other evidence.

The graywackes contain a great number of quartzite beds from 1 to 3 inches thick for about 200 feet above their base. Soft shaly partings between the siliceous layers have weathered out leaving the beds elevated as prominent bands on outcrops. The graywackes have been recrystallized to biotite-garnet schists, and gneisses. Locally sulphides have been introduced.

The overlying 500 feet of sediments are uniformly dark, recrystallized, shaly, graywackes which weather to a characteristic rusty color. This part of the series is heavily injected by fine grained quartz and quartz feldspar pegmatites in which the two minerals are intimately intergrown. Neither type of pegmatite

is known to carry even traces of graphite. The quartzose beds at the base have undergone little change and show only simple recrystallization effects.

This shaly zone grades upward into more massive sediments with beds up to ten feet thick. These thick massive beds are lenticular and in one instance were found to be overlain by cross bedded deposits. The femic constituents have passed to biotite and black hornblende in about equal proportions. Alkali feldspar with a small amount of quartz constitutes the remainder of the rock. At no place, however, is graphite found in the graywacke series at distances over thirty feet above the base.

The Laurentian Intrusives.

Batholithic masses of granite bound the sediments on the northwest and southeast sides. Smaller intrusives and injected pegmatites are found almost everywhere that the Grenville Series is exposed. Almost invariably the longer axis of the intrusive mass parallels the strike of the sediments.

The Granite Batholiths.—The main intrusives northwest and southeast of the area of sediments show banding typical of the Laurentian gneiss. Light colored bands of flesh colored anorthoclase feldspar in equidimensional grains with parallel streaks of almost glassy injection perthite, about 10 per cent. of quartz and occasional grains of sodic amphibole, alternate with dark bands varying in width from the merest film to curtains six inches thick; quartz and alkali feldspar make up about 70 per cent. of this dark rock but biotite and black hornblende are unusually abundant.

Thicker femic streaks are found nearer the sediments. The best examples are on the southeast shore of Lake Louisa. The femic streaks vary from 1 to 6 inches in thickness and are separated by aplite bands up to 6 feet wide. The dark bands instead of being drawn out into long smooth curving planes are intricately crumpled in the same fashion as that phase of the Grenville Limestone, which grades into the underlying graywacke, and which, from the structure of the region, should occur at the above

locality. Faults offset individual and even groups of dark curtains. One aplite injection may be offset, whereas an adjacent one may not, indicating active movement at the time of injection. Reaction between the curtains and the magma greatly diminished the thickness and continuity. Where the strike of the beds was originally more uniform, as in the graywackes, the dark bands follow smoother curves. Since the graywackes form the greater part of the series where the most complete sections are found, and since they are usually intruded more completely than the other by the invading magma, smooth curving streaks are more expectable and more common than the intimately crinkled ones which form from the underlying calcareous graywacke and silicated limestone. The structure of the granite gneiss is therefore regarded as being due to intimate injection, along slaty cleavage or schistose bedding planes of metamorphosed sediments, of an aplitic and pegmatitic magma. Complex faulting comtemporaneous with the aplitic injection has masked the primary origin and composition of the dark streaks.

Smaller Intrusives.—An elongated mass of granite outcrops on the ridge between Boyd Lake and the Middle Branch of the West River. The rock is more massive and coarser grained than the typical Laurentian granite to the northwest and southeast. Dark streaks which are oriented parallel to the strike of the graywacke are very common at the north end of the intrusive; streaks over an inch thick are quite rusty and can be recognized easily as remnants of a curtain which has been almost completely dissolved.

Many dikes follow bedding planes in sediments adjacent to intrusive contacts; those associated with the main batholith are usually characterized by flesh colored feldspar in graphic intergrowth with quartz whereas those from the smaller mass west of Boyd Lake have white feldspars and contain many large phenocrysts. Dikes from both intrusives are coarser grained than the parent rock.

Pegmatites.—Two distinct types of pegmatites are recognized. One type is composed largely of a light-colored feldspar similar

to that in the minor intrusives and the other type is made up of a fine grained aggregate or of a graphic intergrowth of quartz and feldspar or in other cases merely of granular quartz.

The first type of pegmatite is found around Boyd Lake in the vicinity of the minor intrusive rather than with the main underlying batholith. Graphite is found replacing one of these pegmatites so that mineralization is probably associated with the deuteric effects of these injectives. The fine grained pegmatites make up 10 to 20 per cent. of the area of graywacke shown on the map except along either side of the anticline marked by the series of limestone outcrops following the south side of Boyd Lake and eastward to Number 6 deposit. Pegmatites are not common in this zone. The dikes seldom exceed 10 feet in width but they are unusually numerous. No mineralization effects were observed in association with this type.

The abundance of pegmatites is the only measure of the depth of the granite gneiss below the surface; abundant pegmatites may indicate a dome in the roof of the batholith whereas absence may indicate a saddle. The only place where deposits could be expected to continue in depth would be in the saddles because no deposit has been found in, or in contact with, the granite.

Diabases.—Dark olivine diabases of unknown age cut all the rocks of the district. They strike east and west and many small dikes are associated with the main larger one paralleling the road east and west across the graphite area. Another small dike occurs 100 feet northeast of the Number 1 deposit.

STRUCTURAL GEOLOGY.

The area under consideration lies on the western side of the embayment in the structural trend of the Grenville Series.[1] Remnants of the sediments normally strike north and south but along an axis trending about N. 60° W. from St. Jerome, Quebec, they swing eastward into a deep embayment before again resuming their normal course. The sediments of the Louisa graphite area lie on the flanks of a large anticline whose axis passes just

[1] Adams, F. D., Canada Geol. Surv., Ann. Rept. 1895, Pt. J, Map.

north of Boyd Lake. Elliptical areas of limestone mark small crumples upon the flanks of the major structure (Fig. 2). With increasing distance from the main axis, the areas of limestone

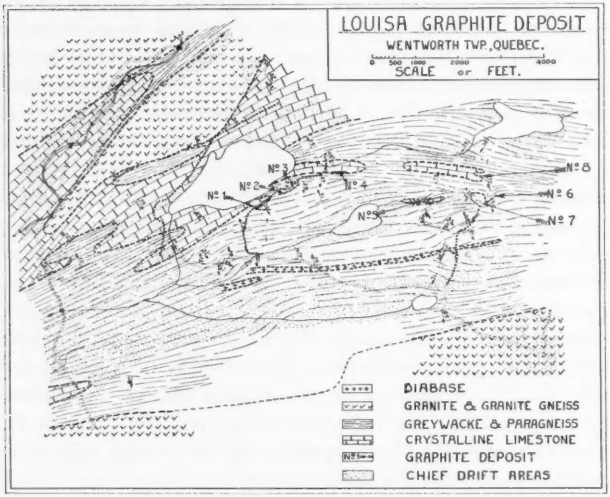

FIG. 2. Geological map of the area in the vicinity of the graphite deposits.

become smaller and persist merely as small unroofed domes. As the sediments are followed eastward, it will be observed that the axes of the individual folds intersect the axis of the main structure. These relations of the limestone outcrops seems to indicate an eschelon arrangement of the folds. Minor folds of this type usually die out very rapidly along the continuation of their axis. Yet, as will be pointed out later in the description of the Number 2 deposit, the limestone is encountered at a depth of 30 feet instead of at about 100 feet, an occurrence which indicates that the anticline which begins near the Number 1 deposit continued far eastward beyond the plunge of the limestone beneath the graywackes. The axial planes of the folds dip about 45° to 60° S.

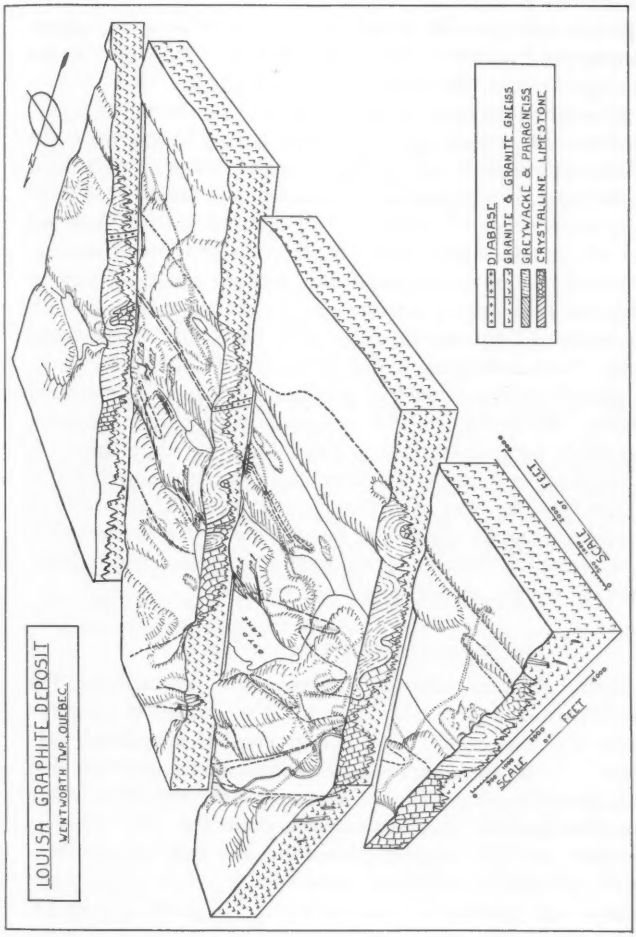

FIG. 3. Block diagram showing the topography, geology and structure in the vicinity of the graphite deposits.

except around the intrusive granite north of Boyd Lake, where dips are usually reversed, probably due to deformation accompanying the invasion of the satellite intrusive (Fig. 3). Major folding of a later date seems altogether negligible.

Abundant pegmatites from the aplitic magma cut the graywackes at all places except in a narrow zone following the strike of the anticlinorium and passing along the south side of Boyd Lake. Quartzose pegmatites become especially numerous ¼ mile south of Number 7. This type of pegmatite is more abundant near the granite contact than farther removed from it laterally. A similar relation is to be expected to hold for a vertical range as well, and a deep sag in the roof of the batholith follows beneath the series of limestone anticlines along the south side of Boyd Lake. Such a structure would give a greater depth of rock to be mineralized than would be possible in a heavily pegmatitized section. Mineralization of a transverse fault cutting the folds and aplitic pegmatites of the sediments, and in which the veins of the Number 1 deposit are found, indicates that mineralization is later than the invasion of the aplitic magma. There seems to be evidence that the graphite is associated with the coarse orthoclase pegmatites from the small granite intrusive north of Boyd Lake but the age of this mass is indeterminate.

DESCRIPTION OF THE DEPOSITS.

General Features.—All graphite occurrences are limited to the central part of the area of sediments and are formed at the graywacke limestone contact or in the graywackes immediately adjacent. All observed deposits are situated on the southern side of a limestone area. The axial plane of the anticlines which bring the limestone to the surface dip southward. All deposits, therefore, are just below or just within the shaly graywackes. As the outstanding structural occurrence, graphite would seem to have been deposited by upward moving solutions (liquids or gases) which were impounded in pockets such as anticlinal summits or beds sealed by a fault or a dike, or, in thin porous beds near the limestone where movement of the solutions was so slow

that replacement could occur during migration of the solutions.

Number 1 Deposit.—Number 1 deposit is a series of veins in a curving fault zone transverse to the strike of the graywackes immediately adjacent to the limestone and dipping 80° SW. Graywacke lies on both sides of the fracture where it is exposed in a prospect pit and trenches. A short distance west, limestone forms the northern side or footwall and graywacke the southern side or hangingwall (Fig. 2). Lateral as well as vertical displacement, as shown by slickensides, has given a resultant downward movement of the hanging wall at about 70° to the west. The beds on the footwall are highly brecciated and bent completely over by the drag. Lenticular and overlapping veins characterize the brecciated zone. An average cross section of the lode from hanging wall to footwall is as follows:

	Graywacke hanging wall heavily slickensided but massive and stands up well.
2 ins.	Brecciated and slickensided graywacke with much quartz.
5 ins.	Zone of graphite veins. Graphite lenses aggregating 1 to 3 inches (average 1½ inches) free from gangue and held between quartz walls. Graphite is in flakes arranged in rosette pattern.
12 ins.	Breccia of graywacke. Much finer gouge.
4 ins.	Quartz graphite vein with ½ to 2 inches of graphite (average ¾ inches). Graphite columnar.
3 ins.	Breccia carrying about 4 per cent. disseminated graphite (flake).
12 ins.	Barren breccia.
2 ins.	Vein quartz with about ½ inch of graphite.
8 ins.	Breccia with 1 to 4 per cent. disseminated flake graphite. Graywacke footwall very weak and crumbly for about 6 inches back from the crush.

Total 48 ins. crush zone.
Total 2¾ ins. graphite vein.
Total 11 ins. disseminated graphite.

The rock of the crush zone is so weak that it can be brought

down by a pick without blasting. Surface weathering may be partly responsible for this weakness. The deposit is exposed for 120 feet east and west. Graphite was found in the trenches at either end, usually in quartz.

Number 2 Deposit.—The Number 2 deposit is intimately associated with a pegmatite injected parallel to the bedding planes of the graywackes southeast of Boyd Lake. Limestone was encountered in the shaft at 30 feet down. The beds dip about 36° S. but in places lie almost horizontal and at others, steepen to 75°. The pegmatite varies greatly in thickness; locally it may be only three or four inches and at other points may thicken to 2 or even 3 feet. White orthoclase feldspar in large crystals ¾ inches across and accessory quartz make up the entire unaltered portion of the dike.

Veins on either margin have approximately equal widths of graphite crystallized perpendicular to the walls; they average about 1 inch but vary from ½ to 2 inches; multiple veins, that is a single vein made up of as many as five minor veins of columnar graphite set one upon another, are most common. Smaller veins up to ⅜ inches across fill many of the fractures in the dike and sometimes spread out into the graywacke and replace certain beds; this, however, is not common.

The pegmatite and the associated graphite veins are exposed by cross trenches and the shaft for 280 feet and the lode continues beyond the trenches at either end. On an average the deposit carries 2 inches of vein graphite and 2 inches of rock containing about 33 per cent. of the mineral.

The margins of the pegmatite and of fractures in it contain occasional radiating masses of green chlorite about ⅛ inches in diameter and is highly mineralized by graphite for a distance varying from almost nothing to 2 inches back from either margin (Fig. 4). The immediate margin is almost completely replaced by graphite and can only be distinguished from the veins by the terminations of the columnar graphite against a smooth surface. Farther in, replacement is not nearly so complete and the central portions of the feldspar crystals remain. The faces of the crys-

tals and the margins of the grains are deeply corroded (Fig. 5) and are completely replaced by flake graphite and by radiating bunches in part pseudomorphous after chlorite. This zone aver-

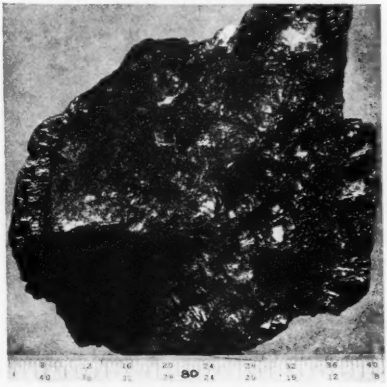

FIG. 4. Photograph showing graphite-bearing pegmatite. Note the columnar graphite along either side, and the disseminated graphite in the right central part of the specimen.

ages about 1 inch wide and contains 33 per cent. graphite. Still closer to the center of the dike, graphite occurs as scattered flakes along the margins of the feldspar grains. Portions of the pegmatite removed from either margin or from fractures, appear quite fresh and show no mineralization effects whatever.

Microscopic examination of the least mineralized portions of the pegmatite shows graphite in secondary pegmatites filling fractures and corrosion chambers in the white orthoclase (Fig. 6) which is unaffected chemically by the later pegmatites. The secondary pegmatites carrying the graphite are composed of quartz and albite in about equal proportions and graphite in variable amounts. The albite is highly sericitized even although the earlier orthoclase is unchanged. The solutions which formed these secondary pegmatites were typically pyrogenetic in composi-

tion and behavior, and were evidently in chemical equilibrium with orthoclase which they were capable of dissolving and replacing but incapable of altering.

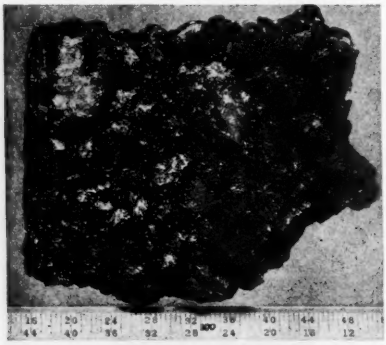

FIG. 5. Photograph of interior of graphite-bearing pegmatite. Corrosion borders between the graphite (black) and the orthoclase (white) are very conspicuous in the upper left part of the specimen.

The fact that the graphite occurs on both sides of the flatly dipping pegmatite and not on the footwall side alone, indicates that the occurrence is not due to concentration beneath an impervious barrier but is due either to solutions following zones of weakness along the margins of the dikes or to part of the pegmatitic magma of the dike, concentrated in fractures, reacting with the already crystallized portions.

Number 3 Deposit.—Number 3 deposit is exposed for about 3 feet in only one trench. Graphite is present as flakes about ⅛ of an inch in diameter disseminated through calcareous graywackes near the limestone contact. The content of the zone is low and the deposit poorly exposed.

Number 4 Deposit.—Number 4 deposit occurs in limestone just below the overlying quartzite and is exposed in a single pit ten feet across and 15 feet deep. The main graphitic zone is about 3 feet wide and contains 3 to 5 per cent. of the mineral

as flake averaging 1/16 inches across. Abundant pyrite accompanies the graphite. The limestone beds through which the graphite is disseminated dip 45° southward beneath the graywackes.

The graphite had two undesirable features; the flake is small and therefore not of the best grade and secondly, much pyrite is associated with it. The separation of sulphides has proved to be exceedingly difficult in other deposits. The pyrite in specimens on the dump is almost completely oxidized and the rock crumbled to a sand. As suggested by Brown,[2] dump weathering of the mined rock might be sufficient to remove the pyrite and free the graphite from the limestone thereby preventing further reduction in the size of the flake.

Number 5 Deposit.—Number 5 deposit is exposed on the crest of an anticline which brings limestone to the surface along a narrow zone exposed for 250 feet by a number of trenches transverse to the strike. The anticline lies south of the axes of any of the other structures on which graphite has been found. Abundant graphite is exposed in either end trench but it is believed that in a short distance the bed plunges beneath the overlying graywackes. The deposit carries 5 to 8 per cent. of graphite over a zone varying from 4 to 8 feet wide. The flake is about 1/8 inch in diameter and free from sulphides making it much more desirable than the number 4 deposit.

The question of the extent of the deposit is one that is closely linked with origin and the structural control of solutions which produced it. Three alternative hypotheses present themselves:

1. The graphite may be original carbonaceous or bituminous material crystallized in place, or nearby, by the agents which effected the metamorphism and recrystallization of the enclosing rock. In this case the extent of the deposit and that of the bed would be practically the same.

2. The graphite may have been produced by the metamorphism of hydrocarbons which had migrated upwards to the crest of the

[2] Brown, John S., "Graphite Deposits of Ashland, Ala.," ECON. GEOL., vol. 20, p. 247, 1925.

anticline. The extent in that instance would be analogous to the extent of the oil in certain oil pools and the deposit would end rather abruptly at a moderate depth depending upon the amount of bituminous matter originally present.

3. The graphite may have been deposited by emanations from the subjacent magma, impounded in pockets on the anticline or deposited from carbon compounds produced by reaction between the emanations and carbonates in the limestone. In this case the deposit might be expected to continue to a much greater depth than in the second instance, but be found only on the upper side of the asymmetric fold.

Gradational contacts of limestones into shales or graywackes are almost invariably characterized by either a graphitoid or a bituminous zone and the contact between the Manhattan schist and Inwood limestone, the Hudson River phyllites and the Wappinger limestone and the Vermont marble zone and the overlying phyllites and graywackes may be cited as examples. The abrupt change in lithology at the top of the Grenville limestone indicates a disconformity and means that the graphitoid zone, if ever present has been eroded away.

The fact that all other deposits are found on the south side of the limestone areas and lie immediately below the hanging wall of impervious graywacke or quartzite, would seem to indicate that they were formed by uprising solutions after the beds had attained their present attitude. If this is the origin, and it seems to be, the graphite, whatever its primary origin, owes its present position to rising solutions impounded beneath the graywacke by an anticlinal fold. Chemical nature, behavior, and origin, of these solutions is better illustrated by deposit Number 6 and is left until then.

Number 7 Deposit.—Number 7 deposit follows a quartzose graywacke bed and the graphite appears to have formed by recrystallization of the original carbonaceous matter of the sediments. Except along a shear zone, the mineral is very fine and makes up too small a portion of the rock to be of economic value.

Number 6 Deposit.—Number 6 deposit lies about 100 feet

north of number 7 and parallels it. The zone is exposed for 325 feet by five trenches and pits and varies from one to five feet wide, averaging about three and one half feet across. Graphite makes up ten to fifteen per cent. of the zone. Flake ranges up to half-inch and is free of sulphides but intimately mixed with uralite. Pockets of massive graphite show coarse, closely packed flakes on breaks.

The rock is a typical skarn of large, prismatic, white pyroxene, and sphene crystals up to one and one half inches across, embedded in a matrix of very coarse flake graphite, and fine grained uralitized diopside. Occasional areas of fresh diopside remain and in these places the rock carries almost no graphite. In other instances masses of graphite a foot in diameter are found in the deposit. Where alteration has not been complete it is seen that the diopside first alters to uralite and chlorite and that graphite replaces these alteration products (Fig. 7). Replacement of pyroxene in these deposits is never a direct process.

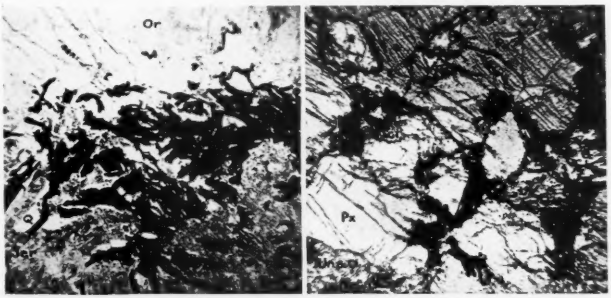

FIG. 6 (left). Photomicrograph of graphite-bearing pegmatite, showing orthoclase (*Or*) cut by narrow dikes of serecitized albite (*Ser*) which are continuous with a larger mass of the same material carrying graphite (black) and quartz (*Q*). Ordinary light, × 35.

FIG. 7 (right). Photomicrograph of graphite-bearing skarn, showing graphite (black) occurring in cloudy areas of uralite (*Ur*) and of uralite and chlorite (*Ur* and *Cl*) which are alteration products of the clear pyroxene (*Px*). Alteration occurs along secondary fractures and grain borders. Ordinary light, × 35.

Knots of tremolite fibres surrounded by the other skarn minerals are common and occasional spherical masses of carbonates surrounded by tremolite were observed. These transitional structures indicate that the deposit was formed in a carbonate rock or limestone bed tightly infolded as an anticline in the graywackes.

The graphite is plainly introduced material and is replacing the earlier silicate minerals notably the uralite and chlorite formed by alteration of pyroxene of the skarn. Intimate relation of the alteration of the diopside and replacement of the alteration products seems to indicate that the same solutions are responsible for both processes. Uralitization of pyroxene is one of the commonest changes produced by magmatic solutions of silici-alkalic composition. The graphite, therefore, is regarded as having been brought in by magmatic solutions of this type. Since the limestone was completely silicated before the graphite was introduced, and since the graphite is found as a replacement of the alteration products of these silicates, the carbon could not possibly be derived from CO_2 liberated by the silication of carbonates original to the limestone but must have been a direct late stage emanation from a magma along with the silici-alkalic solutions producing alteration of the skarn.

AMHERST COLLEGE,
AMHERST, MASS.

EDITORIAL

THE FIFTEENTH INTERNATIONAL GEOLOGICAL CONGRESS.

INTERNATIONAL Geological Congresses differ from other scientific congresses, because technical sessions for the reading of papers occupy only a small part of the period of the Congress. Emphasis is laid instead upon geological excursions into different parts of the host country, so that the region may be studied at first hand in the field. For this reason the Union of South Africa was a happy choice, and it proved of unusual interest to the geologists and mining engineers who attended the meeting there in July and August of this year. Several went early, to see parts of the country in advance of the excursions, many lingered afterwards, and some are only now returning.

This Congress was excellently planned. Great credit is due to its President, Dr. A. W. Rogers; to its efficient Secretary, Dr. A. L. Hall, upon whom most of the labor fell; and to their able committees. Excursions were carefully arranged so as to give visitors the maximum opportunity of seeing and learning something about the Union's unusual geology and outstanding mineral resources. Social functions were subordinated so that the main aim of the Congress was not lost sight of. Nevertheless, the congressionalists were not without opportunity to appreciate the open and hearty hospitality of the communities and of the mining companies. The technical sessions at Pretoria were interspersed with short geological excursions, and this gave the members an opportunity to be all together for twelve days or so without the necessity of devoting that much time entirely to the hearing of papers. One noteworthy feature in the arrangements was that members were enabled to have short trips to certain places of interest covered by larger excursions that ran concurrently with

their own. Thus, one who could not take the long Bushveld excursion was given the opportunity, at a different time, to take a short trip to a part of the Bushveld near Pretoria. Likewise, those who chose the pre-Congress tectonic excursion were not forced to omit the interesting Rand gold deposits of the concurrent economic excursion, because a short excursion to Johannesburg a week later was planned for their benefit. This is a feature that might well be adopted in future meetings.

About 340 registered for the Congress, of whom 260 were visitors from other countries. South Africans, of course, predominated, and next to them were Germans, then Americans, then English. About thirty-nine different countries were represented. It was an unusually interesting group.

Most of the visitors landed at Cape Town, and four short excursions took place from there on July 16 and 17. Then two longer excursions, each of about ten days' duration, left from Cape Town to Pretoria. A–5, planned for those interested in general and structural geology, included the interesting tectonic region between Cape Town and Kimberley. A–6, the star excursion and the most popular, was planned chiefly for economic geologists and mining engineers, to give them an opportunity to study the diamond, gold, and other mineral deposits around Kimberley and the Witwatersrand. This group had a most instructive trip under the leadership of Du Toit, Wagner, Beetz, Shand, Reinecke, and the mine officials. They will particularly recall with pleasure the hospitality of the De Beers Mines and the many excellent specimens this company placed at their disposal. Nor will they ever forget the courtesy of the manager, Mr. Alpheus Williams, and his zeal in giving freely of his own extended observations of the diamond pipes. In Johannesburg, also, the members were royally entertained and given access to representative Rand mines. Needless to say, considerable dispute arose as to the origin of the gold in the banket. Both excursions ended in Pretoria, on July 27. All the members then participated in a one-day orientation excursion around Pretoria on July 28, when a glimpse of a fringe of the Bushveld was obtained.

The Congress formally opened in Pretoria on July 29, and on

the following day the reading of papers began. Several sectional meetings, unfortunately poorly attended, got under way. Some of the topics were: The Rift Valleys of Africa; Pre-Pleistocene Glacial Periods; the Karroo System; Magmatic Differentiation; Geophysical Methods; The Genesis of Petroleum; Gold Resources of the World; the Genesis of Micro-organisms.

During the Congress, Excursion B–8 to Johannesburg for three days starting July 31, gave those who could not join A–6 an opportunity to see the gold mines. Another interesting and very popular excursion on the same day, B–9, was a one-day trip to the remarkable Rustenberg platinum mines, where we saw a thin persistent platiniferous chromite band resting on white anorthositic norite below and overlain by the Merensky reef. We also saw supergene platinum enrichment. An extension of the trip for another day took in the varied alkaline ring intrusions of Pilandsberg. B–10 also gave opportunity to see the alkaline rocks of Franspoort. On Sunday, August 4, B–11 supplied a one-day trip to the Pretoria Salt Pan, where we saw a remarkable explosion caldera about 3,400 feet in diameter and 300 feet deep, the rim of which rises only about 100 feet above the surrounding flattish country. A part of the floor is covered by a soda-salt brine from which commercial salts are extracted. A concurrent excursion (B–12) afforded another opportunity to see a different part of the fringe of the Bushveld. Two other short excursions during the Congress took in the Pretoria iron mines and the famous Premier diamond mine. At the latter, we saw the "greatest hole in the world" and listened to 3,000 blasts going off in two minutes.

The formal meetings ended on August 7, and on the next day those interested in tectonics were thrilled by a three-day trip to the classic Vredefort Dome, where a dome-like granite intrusion is surrounded by a perplexing ring of sediments that dip toward it. A concurrent excursion to the Devil's Kantoor provided a view across the great Eastern Escarpment and a trip through the rich Amianthus chrysotile asbestos mine. The remarkable rhythmic banding of the thin chrysotile seams over several feet in thickness of serpentine puzzled everyone.

Then came the breaking up of the Congress as a whole. The members parted for their several long return excursions. Some returned to Cap Town via the Port Elizabeth excursion (C–17) or the Durban-Zululand excursion (C–18) to see the stratigraphy of the South. An interested group braved, with good fun and much banter, the hardships of the choice Bushveld excursion (C-19) where the norite made hard beds and the nights were cold. But they were compensated. Ten days under the able and congenial leadership of Hall, Nel, and Shand, disclosed magmatic differentiation on a grand scale that produced chromite and magnetite and platinum beds. But as to how they had formed, Niggli had his ideas, Reuning voiced multiple intrusions, Bowen disagreed, and Grout quietly smiled. We saw also the unique platinum and tin pipes, and other mineral deposits. The members of this excursion presented Dr. Hall with an engraved smoking set as a token of their appreciation of his efforts in their behalf. The lure of Victoria Falls led most to choose the Rhodesia excursion (C–20). Under the leadership of Mr. Maufe the party, traveling in sleeping cars, visited the interesting Shabani asbestos deposits, the famous Selukwe chromite bodies, gold and coal mines, and the Great Dike, ending at Victoria Falls. A continuing excursion (C–22) enabled a small group to visit Northern Rhodesia.

The itinerary of the excursions gives only a slight indication of the many diversified geological features that were made available. The country is rich in interest for the economic geologist, the petrologist, the structural geologist, and the mining engineer. Nowhere else can be seen so many unique types of mineral deposits or so many problems that still await solution, despite the excellent work that has already been done upon them.

All those who were so fortunate as to attend this Congress have come back with a realization of the great contributions South Africa has made and will continue to make to our geological knowledge and to our mineral wealth. The world has long known about its great diamond and gold deposits, but it little realizes South Africa's wealth in chrome, platinum, asbestos, manganese, iron, and corundum. As a country of potential ores, it will vie with Northern Canada and Siberia. And its neighbors

to the north, Northern and Southern Rhodesia, are likewise rich mineral regions. Southern Rhodesia already leads the world in chrome production. It also contains large and rich asbestos deposits; its coal supplies lower and central Africa; and its gold production has long been a valuable asset to the British Empire. Northern Rhodesia is just being developed. Stupendous copper deposits are already being exploited and before long it will be one of the great copper-producing countries of the world.

The members of the Congress are unanimous in agreeing that the Fifteenth Session in the Union of South Africa was a great success. But this success is due not alone to South Africa's interesting geological phenomena, nor to its unique mineral deposits, but in large measure to the capable local committee, to the indefatigable work of Dr. Hall, and to the hospitality, generosity, and courtesy of the mining companies who opened their mines, their pocket books and their hearts. We sincerely hope that the next Congress, which is to come to the United States in 1932, may be as successful.

ALAN BATEMAN.

DISCUSSION AND INFORMAL COMMUNICATIONS

THE ORIGIN OF ARTESIAN PRESSURE.[1]

Sir: The recent paper by W. L. Russell on the origin of artesian pressure[2] is a valuable contribution to ground-water literature, particularly because it has invited attention to a reconsideration of the information available in regard to the great so-called Dakota artesian basin in the light of present knowledge of ground-water hydrology. As long ago as 1890 it was suggested that the artesian pressure on some water-bearing strata may be due in part to the weight of the overlying rocks,[3] and since that time several persons have advanced the idea.[4] That the pressure of overlying rocks, and even of changing volumes of water at the surface in the form of tides, can be readily transmitted to the water confined in some aquifers has been conclusively demonstrated in a number of ways.[5]

There is little doubt that the water in the Dakota sandstone bears part of the weight of the overlying rocks. Meinzer assumed this to be true in explaining certain conditions of the hydraulic head on the sandstone in southeastern North Dakota.[6] Russell, however, goes further and considers that the artesian pressure of the water is due wholly to the weight of the overlying rocks. This postulate is based largely on stratigraphic evidence

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] ECON. GEOL., vol. 23, pp. 132–157, March-April, 1928.

[3] Hay, Robert, "Artesian Wells in Kansas and Causes of their Flow," *Amer. Geologist*, vol. 5, pp. 296–301, 1890.

[4] See references by Meinzer, O. E., "Compressibility and Elasticity of Artesian Aquifers," ECON. GEOL., vol. 23, pp. 265–266, 1928.

[5] *Idem*, pp. 266–277.

[6] Meinzer, O. E., and Hard, H. A., "The Artesian Water Supply of the Dakota Sandstone in North Dakota, with Special Reference to the Edgeley Quadrangle," U. S. Geol. Survey, Water-supply Paper 520, pp. 90–93, 1925.

that the beds assigned to the Dakota sandstone in the eastern part of the basin are not contemporaneous with beds in the Black Hills region which have generally been assigned to the same formation. He believes that the sandstones of the Dakota formation have no connection with the beds that crop out in the Black Hills region, for which he proposes the name Fall River formation; or at least that these sandstones are so lenticular and disconnected as to inhibit extensive artesian circulation. Russell's conclusions seem to depend largely on a study of outcrops in localities separated by the entire width of the State of South Dakota. To prove his contention from well logs is a difficult task, and this he admits. But in further support of his hypothesis Russell cites additional data in regard to the distribution of artesian pressure on the water in the sandstone, variations in the quality from place to place, etc. Russell's hypothesis is plausible, and, if his interpretation of the conditions described by him is correct, it must be the true explanation. It is the belief of the writer, however, that essentially every condition he cites can be explained in some other way. Alternative explanations of some of the facts cited by Russell have already been presented by Piper [7] and Terzaghi.[8] The phases of the problem covered by them need not be discussed here.

Since 1923 the writer has been engaged in studies of the quantity of water available from certain more or less prolific water-bearing formations. This work has involved a rather intensive study of the fluctuations of the head on the water in artesian aquifers and a comparison of present conditions with those when the aquifers were first tapped. It is on the basis of the information gained in these studies that the writer wishes to discuss especially Russell's statements as to head.

It is first desirable to recall certain well-known phenomena resulting from the pumping of wells or the discharge of water by natural flow. As soon as the withdrawal of water begins the

[7] Piper, A. M., "The Origin of Artesian Pressure," ECON. GEOL., vol. 23, pp. 683–696, Sept., 1928.

[8] Terzaghi, Charles, "The Origin of Artesian Pressure," ECON. GEOL., vol. 24, pp. 94–100, Jan.-Feb., 1929.

pressure or head on the water decreases—at first rapidly and then more slowly until a condition of stability is reached. The loss in head is, in general, approximately proportional to the rate of withdrawal of water. Furthermore, there is a loss of head not only in the well but in all directions in the formation surrounding the well, the amount of loss becoming less and less as distance from the well increases.

Where wells flow naturally under artesian pressure the same principles hold, but the head is generally measured as pressure at the surface instead of the level to which the water would rise if a pipe were extended into the air. As soon as any water is allowed to escape from the well the pressure at the outlet is diminished. The difference between the flowing pressure and the static pressure represents the drawdown. As in a pumped well, there is a loss in head on the water in the formation in all directions from the well, and thus the pressure on near-by wells decreases.

The typical profile of the piezometric surface, or imaginary surface connecting the points to which the water would rise in wells penetrating the formation, is similar to that of an inverted cone, except that lines drawn from the apex to the base have the shape of a hyperbolic curve. Theoretically the curve rises, always with a lessening gradient, to an infinitely great distance from the pumped well, or at least to a point where the recharge is equal to the discharge from the aquifer. The distance at which the departure from the original head does become negligible differs in different formations. It has commonly been considered that the decline in head becomes negligible only a few hundred feet from the well. For example, in one text it is stated: "It will be sufficiently accurate in most cases to take an arbitrary value of R, such as 1000 feet," R being the radius of the circle of influence, or circle where the loss in head is appreciable.[9] Observations by the writer in several different localities lead him to believe that the area in which the head declines measurably is greater than has been supposed for formations whose water-bearing capacity is low. The radius of the circle of influence has

[9] Turneaure, F. E., and Russell, H. L., "Public Water Supplies," 3d ed., pp. 256, 259. John Wiley & Sons, 1924.

been found to range from a few hundred feet in a formation whose permeability was considered to be high to more than half a mile in one whose permeability is low. When several wells are flowing or being pumped the combined area of influence will be extended even farther than the limits given. For example, in the Atlantic City region of New Jersey the head on the so-called 800-foot sand has been lowered from a few feet to as much as 100 feet in an area that extends some 40 miles along the coast, at least 10 miles inland, and probably as far beneath the ocean.[10] This is largely the result of pumping about 10,000,000 gallons a day from about 25 wells in Atlantic City or within 5 miles of the city, and only a negligible amount of pumping on the outer edge of the area. In the Asbury Park region the head on the Mount Laurel and Wenonah sands has decreased a maximum of nearly 120 feet as a result of a total pumpage of less than 2,000,000 gallons a day.

A significant fact observed in every region where the writer has made detailed studies is that when a given rate of draft was imposed on an artesian aquifer the maximum loss of head resulting therefrom was not reached immediately.[11] In the formations whose permeability is high a condition of apparent stability is reached in a few hours, but in those whose permeability is medium or low the stability is not reached for periods of a few days to a month or two. The change in head from day to day may be sometimes only 1 or 2 inches. Nevertheless automatic water-level recorders showed the change to be accumulative and in the long run to amount to several feet.

The water-yielding capacity of a well, which is frequently used as an approximate index of the permeability of the aquifer, is commonly determined by its "specific capacity," or yield in gallons per minute per foot of drawdown. This quantity is rather indefinite because the drawdown for a given yield varies not

[10] Thompson, D. G., Ground-water Problems on the Barrier Beaches of New Jersey," *Bull. Geol. Soc. Amer.*, vol. 37, pp. 466–467, 1926; "Ground-water Supplies of the Atlantic City Region," New Jersey Dept. Conserv. and Devel. Bull. 30, pp. 68–74, Fig. 15, 1928.

[11] New Jersey Dept. Conserv. and Devel. Bull. 30, pp. 42–54, 66, 1928, and unpublished studies in other areas.

only with different kinds and thicknesses of water-bearing material but also with different types of well screen, different lengths and diameters of casing and screen, and other factors. If enough data are available these factors can be evaluated, and fairly accurate comparisons of different formations can be made. So far as the Dakota sandstone is concerned the published information is unsatisfactory and it is not possible to compare the water-bearing capacity of this formation very accurately with that of the formations with which the writer is familiar.

The great pressure in many wells in the Dakota sandstone and the large yields of some of them give the impression that the permeability of the sandstone is high, but a careful examination of the available data does not confirm this impression. The famous well at Woonsocket, S. Dak., which was 6 inches in diameter, is said to have yielded 1,150 gallons a minute, but to produce this quantity a loss of head, or drawdown, of about 130 pounds to the square inch (300 feet) was required.[12] The specific capacity of the well was thus only 4 gallons a minute. A few other wells in South Dakota, reported by Darton, had specific capacities as high as 10 to 15 gallons a minute, or higher;[13] but many, especially those of small diameter, had capacities as low as 1 and 2 gallons a minute and even less.[14] Specific capacities reported by Meinzer for wells in the Dakota formation in the Edgeley quadrangle, just across the line in North Dakota, range from only 3.62 gallons a minute for a 6-inch well to 0.14 gallon for a 1-inch well. As compared to these figures, the specific capacity of wells 4 to 8 inches in diameter pumping from the 800-foot sand at Atlantic City ranges from 10 to 30 gallons a minute. From these data it appears that the permeability of the Dakota

[12] Darton, N. H., "Geology and Underground Waters of South Dakota," U. S. Geol. Survey, Water-Supply Paper 227, p. 134, 1909.

[13] *Idem*—for example, p. 70, well of city of Tyndall and well at Springfield mill; p. 94, wells of city of Armour and Wilson and county well.

[14] *Idem*—for example, p. 66, Plankintown Township well, Crystal Township well, well of A. D. Dongan, and well of J. D. Barton (specific capacity only 0.54 gallons a minute). See also Turneaure, F. E., and Russell, H. L., "Public Water Supplies," 3d ed., p. 266, 1924, giving specific capacities as low as 0.11 gallon a minute for wells in the Dakota sandstone.

sandstone is at best no greater and is probably less than that of the 800-foot sand at Atlantic City. Therefore it is reasonable to believe that the effects of withdrawal of water from the Dakota sandstone either by pumping or by natural flow will be at least as great as those observed on the 800-foot formation at Atlantic City and perhaps in places will be even as great as the effect on the Mount Laurel and Wenonah sands in the Asbury Park region.

With these facts in mind let us consider the statement of Russell that "when the distribution of the pressure in the Dakota sandstone is examined critically, some conditions are disclosed which are difficult to explain by the old theory that the decrease in head toward the east is due to the work done in forcing water through the sandstone." He first states that if the water came from the Black Hills the lines drawn through points of equal head (isopiestic lines)[15] on Darton's map[16] should curve around the Black Hills and that this curvature should be apparent not only in South Dakota but also in North Dakota and Nebraska.[17] As a matter of fact, on Darton's map the isopiestic lines do bend around and follow closely the east side of the Black Hills. Russell appears to overlook the fact that the rocks that in the past have been called Dakota crop out not merely in the Black Hills but along the front of the Rocky Mountains from Arizona to Montana.[18] Regardless of whether the beds that crop out are called Dakota or Fall River, and even if they continue eastward for several hundred miles, as has been commonly believed, with so extensive an intake area the influence of the outcrops around the Black Hills would hardly be expected to extend into either North Dakota or Nebraska, and inflow from these States would tend to straighten the lines in the eastern part of South Dakota.

Russell's statement, however, warrants a close study of the data on which the contour map of the piezometric surface is based.

[15] Meinzer, O. E., Outline of Ground-water Hydrology," U. S. Geol. Survey, Water-Supply Paper 484, p. 38, 1923.

[16] Darton, N. H., "Geology and Underground Waters of South Dakota," U. S. Geol. Survey, Water-Supply Paper 227, Fig. 3, p. 61, 1909.

[17] Russell, W. L., *op. cit.*, p. 141.

[18] Meinzer, O. E., "The Occurrence of Ground Water in the United States," U. S. Geol. Survey, Water-Supply Paper 489, p. 268, 1923.

According to Darton's more detailed map,[19] in the large area between the Missouri River and the Black Hills—from the northern to the southern boundary of South Dakota—the "Dakota" sandstone was reached only in wells at Wendt, Capa, and Nowlin, on the Chicago & Northwestern Railway; at Murdo-McKenzie, Vivian, and Kennebec, on the Chicago, Milwaukee & St. Paul Railway; and on the Rosebud Indian Reservation. Nowlin, the nearest of these places to the Black Hills, is nearly 100 miles from them. Furthermore, no wells from which the head on the sandstone might be determined had been drilled along the eastern edge of the Black Hills between Sturgis, on the northeast, and Minnekahta, at the south end, a distance of more than 80 miles. In the opinion of the writer, considering the structure in the vicinity of the Black Hills and Russell's statements in regard to the lenticularity of the Fall River sandstones, the data are not sufficient to warrant any statement as to whether the true isopiestic lines do or do not curve around the hills.

Russell also states that the isopiestic lines do not curve around the area where the Dakota sandstone crops out in the southeast corner of South Dakota. Here, as in the western part of the State, Darton's map shows a lack of definite data at critical points, and throughout an area along the whole length of the State, from 25 to 75 miles in width, except for wells at Milbank and Browns Valley, there is no basis for a determination of the original head. However, Russell admits that water might even percolate slowly through the shales overlying the Dakota sandstones.[20] If there is any such percolation—and it would presumably be greatest in the eastern part of the State, where the cover is thinnest—even if the beds were completely concealed where they abut against the Paleozoic rocks, the piezometric lines might follow rather closely the outline of the eastern limit of the aquifer, regardless of its outcrop. One thing is certain—namely, that the line of lowest head on Darton's map is near the outcrop of the Dakota sandstone in the southeast corner of the State.

[19] Darton, N. H., *op. cit.*, pl. 11.
[20] Russell, W. L., *op. cit.*, p. 153.

Russell points out certain peculiarities of the isopiestic lines on Darton's map which he believes can not be explained if the water in the Dakota sandstone is moving from the western part of the State.[21] Among these are the facts that the head is lower in the large valleys than on the adjacent uplands, and that in certain places the pressure increases toward the east. He might further have mentioned an asymmetric inverted funnel-shaped depression of the piezometric surface around the city of Huron. He considers that leakage through the overlying strata or around well casings and difference in the draft from place to place are not adequate as possible explanations of the phenomena mentioned, but he presents no data to show just how great the influence of these factors may be. The facts that the writer has obtained in his studies of fluctuations of head in water-bearing formations in New Jersey lead him to believe that the peculiarities mentioned by Russell can be explained by the very factors that he discards.

Here again it becomes necessary to consider the data from which the piezometric lines on Darton's map [22] were drawn. This subject is not discussed in the report that contains the map, but the writer is informed by Dr. Darton that the available data in regard to head were unavoidably of various degrees of reliability. Some were obtained during the course of his own investigations in the period from 1895 to 1903, but many of them were taken from a report by Nettleton based on work done in 1890–91.[23] Some of the pressures in Nettleton's report are quite evidently those existing several years prior to the time of his investigation and possibly as far back as the completion of the first wells in 1882.

In the early days of nearly every large artesian basin it has been the common practice to let wells flow continuously, much water going to waste. This was undoubtedly true in Dakota Territory, and the waste continued in such alarming proportions that laws have been passed prohibiting unnecessary waste, in South Dakota

[21] *Idem*, pp. 142–144.

[22] Darton, N. H., *op. cit.*, pl. 11.

[23] Nettleton, E. S., "Artesian and Underflow Investigation," 52d Cong., 1st sess., Ex. Doc. 41, pt. 2, 1892.

in 1919[24] and in North Dakota in 1921.[25] The following examples may serve to show the great discharge from some of these wells. A well at Hitchcock, S. Dak., drilled in 1885, is said to have flowed constantly for six years up to the time Nettleton made his investigation.[26] He reports the pressure on the well to have been 154 pounds to the square inch and the yield 1,240 gallons a minute (nearly 1,800,000 gallons a day). A well drilled at Huron in 1886 flowed continuously for at least five years,[27] and the static pressure was 120 pounds to the square inch. A well drilled at Springfield in 1891, with a static pressure of 86 pounds to the square inch, flowed 3,290 gallons a minute (4,750,000 gallons a day) and was used to furnish power for a 100-barrel flour mill.[28] A well at Woonsocket, drilled in 1890, had a static pressure of 125 pounds to the square inch. The yield is not stated, but the water was discharged through a 2-inch nozzle under a pressure of about 90 pounds to the square inch to drive a 4-foot Pelton water wheel, which furnished the power for a 125-barrel flour mill.[29] The reports of Nettleton and Darton contain records of many other wells that were used to operate mills, to generate electricity, or for public supply or irrigation and of wells that were allowed to waste large quantities of water. Doubtless there were also many wells not reported by these investigators.

Such great discharges indicate that with little doubt there had been considerable decline in head in some parts of South Dakota, even prior to the time when Nettleton made his field investiga-

[24] Berg, John, "Artesian Waters in South Dakota," South Dakota State Engineer Conservation Bull., November, 1924.

[25] Simpson, H. E., "The Conservation of Artesian Water," North Dakota Geol. Surv. Bull. 5, pp. 12–14, 1926.

[26] Nettleton, E. S., *op. cit.*, p. 42. Nettleton's statements in regard to this and other wells do not indicate clearly whether the pressure and yield are those existing when the well was completed or when he made his investigation. The fact that the present tense is used in certain statements in his report suggests that the recorded pressures and yields are based on tests made by him. If so, the original pressures may have been even greater than he reports.

[27] *Idem*, p. 42.

[28] *Idem*, p. 45.

[29] *Idem*, p. 59.

tion. Furthermore, considering the relative permeability of the Dakota sandstone and of formations studied by the writer in New Jersey, it is his opinion that in some parts of South Dakota the draft was sufficient to cause the decline to extend over large areas. There is abundant evidence that great loss of head has taken place in different parts of the State. Derr [30] reports, for example, in 1915 a pressure at Groton that was 99 pounds (229 feet) less and at Columbia a pressure that was 130 pounds (300 feet) less than those reported by Nettleton for the same places. The typical curve of the drawdown in pumped or flowing wells shows that the greatest loss in head occurs within a short time—a few hours, days, or weeks, depending upon the quantity involved and the permeability of the aquifer—after the draft begins. Therefore it is entirely possible that some of the unusual features of the isopiestic lines on Darton's map are due to loss of head, irregularly distributed, before the first careful observations—those of Nettleton—were made.

In all the localities where unusual bends in the isopiestic lines are shown on Darton's map, with one exception, there were many wells, and accordingly a heavy draft from the Dakota sandstone. It is therefore not surprising that in these localities the head had been lowered in such a way as to produce the irregularities. Furthermore, the departure of the isopiestic lines from their expected direction in the valleys may be attributed to the fact that the wells in the valleys were at lower altitudes than those on the uplands, and the pressure at the surface was accordingly greater, the discharge from the wells probably greater, and the effect on the head in proportion. The irregularities in the head in Potter County in 1927, as shown in Fig. 2 of Russell's paper, may be due to differences in the discharge from wells at low altitudes near the Missouri River and at high altitudes farther east, where much of the water must be pumped. Unless

[30] Derr, H. M., South Dakota State Engineer Rept. for 1915–1916. Derr refers to the higher pressures as being those existing in 1906. Apparently these are based on Water-Supply Paper 227 (p. 73). However, identically similar data are contained in Nettleton's report (pp. 48, 50, table facing p. 74), so that the loss of head occurred over a period of 25 years instead of 9 years as indicated by Derr. Even so, the decline was between 9 and 12 feet a year.

data in regard to discharge from the wells are available the heads shown in Russell's Fig. 2 can not be properly evaluated The single locality where the irregular course of the isopiestic line can not be explained by discharge from many wells is in the vicinity of Harrold and Highmore. A big loop in the 1,900-foot line appears to be based largely on a single pressure record at Harrold.

Russell states that for an east-west distance of 25 to 50 miles in areas east of the Missouri and James Valleys the head is the same and consequently there can be no flow of water across such areas.[31] It should be remembered, however, that with a 100-foot contour interval of the isopiestic lines, the hydraulic gradient might locally have between two contours a considerable slope in any direction. Presumably Russell refers to conditions such as are shown on Darton's map in the vicinity of Harrold, Chandler, Mitchell, and Huron. The isopiestic lines in these localities actually show hydraulic gradients in southeasterly or southerly directions. In no way, however, do the local gradients vitiate the theory of a general eastward movement of the water.

If the writer correctly understands him, Russell believes that the artesian head on the water in the Dakota sandstone is due to the weight of the rocks that overlie the sandstone and accordingly from place to place it should vary approximately as the thickness of the overlying beds. A study of the data relating to head during the early history of artesian wells in South Dakota does not show any such relation. In the following table are given the depth to the top of the principal water-bearing sands, the head above the top of the sand, the ratio of head to depth, and other data in regard to 25 wells in South Dakota. The data are taken from the report by Nettleton, except those indicated as being taken from Darton's report.

The data in the table are arranged in the order of increasing depth, except that data for two wells of different depths at the same town are placed together. A study of the table shows that

[31] Russell, W. L., *op. cit.*, p. 142.

TABLE I.

DATA IN REGARD TO 25 WELLS IN SOUTH DAKOTA.

Depth to Top	Hydrostatic Head.	Ratio Between	Altitude Above Sea Level (Feet).	Distance

TABLE I.

DATA IN REGARD TO 25 WELLS IN SOUTH DAKOTA.

Owner or Location of Well.[a]	Depth to Top of Main Aquifer (Feet).	Hydrostatic Head.		Ratio Between Head and Depth to Aquifer.	Altitude Above Sea Level (Feet).		Distance from Longitude 97° (Miles).
		Above Surface (Pounds).	Above Top of Main Horizon (Feet).		Top of Well.	Hydrostatic Head.	
Wilcox well, Yankton	432	55	559	1.29	1,168	1,295	20
City well, Yankton	610	18	652	1.07	1,259	1,301	20
Letcher	570	90	778	1.36	1,300	1,508	60
Woonsocket	684	130	984	1.44	1,308	1,608	65
Plankinton	740	91	950	1.28	1,521	1,731	75
Chamberlin[b]	780	55	907	1.16	1,547	1,674	115
	785	122	1,067	1.36	1,547	1,829	115
White Lake	850	35	931	1.10	1,650	1,731	85
Iroquois	850	67	1,005	1.18	1,403	1,558	35
Chicago, Milwaukee & St. Paul, Ry., Aberdeen	910	100	1,141	1.25	1,300	1,538	75
Beard well, Aberdeen	1,000	138	1,319	1.32	1,303	1,622	75
Redfield	944	177	1,353	1.43	1,300	1,709	75
Columbia	964	160	1,334	1.38	1,315	1,685	65
Kimball	988	122	1,270	1.29	1,781	2,063	100
Andover	1,070	65	1,220	1.14	1,505	1,655	45
Ipswich	1,230	106	1,475	1.20	1,531	1,776	100
Cheyenne Agency[c]	1,317	205	1,791	1.36	1,500	1,970	165
Harrold	1,435	27	1,497	1.04	1,800	1,862	140
Highmore	1,537	12½	1,566	1.02	1,900	1,929	120
McClure well[d]	1,555	20	1,601	1.03	1,917	1,963	
Nowlin[e]	1,770	72	1,936	1.09	1,964	2,130	210
Gettysburg[e]	1,780	(e)	1,672	.94	2,082	1,974	145
Draper[e]	1,875	(f)	1,675	.89	2,230	2,030	180
Murdo-McKenzie[e]	2,135(?)	(g)	Less than 2,135	Less than 1.00	2,318	Less than 2,318	185
Rosebud Reservation[e]	2,295	(h)	1,795 or less	.78 or less	2,626	2,126 or less	180

[a] City well, unless otherwise stated.

[b] Pressure given for two different depths. See Nettleton, E. S., *op. cit.*, p. 53. The flow from the depth of 780 feet was only 7½ gallons a minute, with a pressure (or drawdown) of 55 pounds; that from the depth of 785 feet was 529 gallons a minute, with a pressure of 122 pounds. [c] From Darton, N. H., Water-Supply Paper 227.

[d] In sec. 31 or 32, T. 108, R. 78, Lyman County. (See Water-Supply Paper 227.) [e] Static head 108 feet below surface.

[f] Static head 200 feet below surface. [g] Did not flow, but depth to water not given. [h] Static head 500 to 600 feet below surface.

there is considerable variation in the ratio between the head, measured from the top of the principal aquifer, and the depth to the aquifer. This is shown especially by a comparison of wells in the same locality. For example, at Yankton the head on the Wilcox well was relatively greater than that on the city well, although in the city well the water apparently came from a deeper stratum. On the other hand, at Aberdeen the head was relatively greater in the deeper of two wells. A striking condition is found at Chamberlin, where, according to a very definite statement by Nettleton,[32] there was in the same well a difference of 67 pounds (155 feet) on the head of water from two depths only 5 feet apart. Obviously, although one of these pressures may be due in large part to the weight of the overlying rock, some other factor is greatly affecting the other one.

The specific examples just discussed are perhaps of most value in calling attention to the fact that because of possible variable factors the data as to relation between depth of well and static head must be used with caution in attempting to discover any relation that may be ascribed to the weight of the overlying rocks. However, on the assumption that most of the data may be used with a reasonable assurance that they are of comparable value, it is worthy of note that in general the deeper the well the less is the ratio of head to depth. This is shown particularly by several wells in the central part of the State. The table includes eight wells that range in depth from 1,435 to 2,295 feet, and in all except one or two of these wells the ratio of head to depth decreases with increasing depth, from slightly more than 1.0 to 0.78. This is contrary to the relation that would be expected according to Russell's theory that the weight of the overlying rock is the only factor in producing the great head on the Dakota sandstone.

The writer does not wish to give the impression that he does not believe that the weight of the rock is partly supported by artesian pressure. On the contrary, it is his opinion that the recent work of Meinzer and others in regard to the elasticity and

[32] Nettleton, E. S., *op. cit.*, p. 53.

compressibility of water-bearing formations has shown that these factors, which are related to the weight of the rocks, are of much more importance than has been realized in the past; and there is opportunity for much further useful investigation of these phenomena, in so far as they affect the permeability of an aquifer. It is the opinion of the writer, however, that Russell's postulate that the artesian pressure on the Dakota sandstones is due to the weight of the rocks alone has not been conclusively demonstrated.

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THE IDENTITY AND GENESIS OF LODESTONE MAGNETITE.

Sir: Dr. W. H. Newhouse presents his opinion on the identity and origin of lodestone in your journal under the title given above.[1] His conclusions rest on two discoveries: (1) The finding of one natural specimen of ferromagnetic ferric oxide in the form of a light chocolate brown powder as described by Sosman and Posnjak,[2] and (2) the discovery of "brownish oxidized magnetite" in polished sections by Newhouse and Callahan.[3] This brownish magnetite is difficult to distinguish from the bluish variety, according to the authors, unless both kinds are in the same section. No analysis has ever been made of it. Hesemann[4] apparently reports similar material but I have not been able to obtain his paper. P. A. Wagner[5] writes of the South African norites: "It soon became apparent that in some of the most strongly magnetic varieties of the ore magnetite is absent, its place being taken by a very strongly magnetic form of ferric oxide that, except for the color of its streak, has all the properties of ordinary magnetite." A reference by H. Schneiderhöhn to the same specimens

[1] ECON. GEOL., vol. 24, pp. 62–67, 1929.

[2] *Jour. Wash. Acad. Sci.*, vol. 15, p. 332, 1925.

[3] Two Kinds of Magnetite? ECON. GEOL., vol. 22, pp. 629–632, 1927.

[4] Hesemann, J., "Die devonischen Eisenerze des Mittelharzes," *Abhandl. zur prakt. Geol. u. Bergw.*, Bd. 10, pp. 38–42, 1927.

[5] ECON. GEOL., vol. 22, p. 846, 1927.

of Wagner [6] claims that this magnetic material is identical in color with hematite as seen under the microscope but its structure seems to be that of magnetite. There would be then *three* colors of magnetic iron oxide as seen under the microscope.

Wagners material is in "intimate intergrowth" with ilmenite. How can this be reconciled with Newhouse and Callahan's [7] statement that "all the bluish magnetites tested show traces of titanium," and the statement of Ramdohr [8] that with an increase of ilmenite the color of magnetite becomes more strongly "braunrosa." He does not report any brownish "oxidized" magnetite in any of his papers. F. F. Osborne [9] writes: "In the titaniferous magnetite studied by the writer there is no evidence of variation in color due to oxidation."

I reëxamined practically all the polished magnetite specimens (at least 100) in our laboratories but found no brownish "oxidized" magnetite. Many different districts were included in this study, among them a number mentioned by Newhouse and Callahan. It would be desirable to receive additional information from other investigators.

I do not doubt that natural magnetite can be oxidized artificially and still retain nearly all its physical properties. In all my experiments, however, on the very slow oxidation of magnetite at not over 200° C.[10] it was easy to recognize the product as hematite. This I have also checked lately with polarized light.

Sosman and Hostetter [11] also made a similar observation. They write: "Slow oxidation of natural magnetite at 400° to 500° yields a non-magnetic oxide, as is evident from Nos. 242, 240, and 224, all of which have a susceptibility in normal agreement with their ferrous iron content."

[6] This is an abstract in *Neues Jahrb.*, 1928, Referate, p. 368.

[7] *Op. cit.*

[8] Ramdohr, Paul, "Beobachtungen an Magnetit, Ilmenit, Eisenglanz, etc.," *Neues Jahrb.*, Beil. Bd. 54, pp. 335–36, 1926.

[9] "Certain Magmatic Titaniferous Iron Ores and Their Origin," ECON. GEOL., vol. 23, p. 911, 1928.

[10] "Magnetite-Martite-Hematite," ECON. GEOL., vol. 21, p. 375, 1926. Also ECON. GEOL., vol. 22, pp. 744–746, 1927.

[11] *Trans. Am. Inst. Min. Eng.*, vol. 58, p. 423, 1918.

Could this indicate that only rapid oxidation (within a few hours) produces ferro-magnetic ferric oxide?

It may not be generally known that an ordinary horseshoe magnet when drawn over a piece of magnetite (best over a smooth section) induces considerable magnetic polarity or remanence in the specimen. The material becomes lodestone. A powerful electro-magnet is much more efficient. Various tests showed that some magnetites have a much greater remanence than others, depending probably on size and shape of specimens as well as on size and arrangement of grains. The polarity does not seem to diminish appreciably within several weeks. In the examination of specimens the following procedure was used: The polished surface was brought in contact with powdered iron (reduced by hydrogen). If powder adhered in spots, they were examined under low and high power. Any specimen that showed no polarity was brought in contact with a horseshoe steel magnet and the attraction for iron powder was noted afterwards. Many of the specimens showed remanence in areas before they were ever brought near a magnet. But in every case only one color of magnetite could be detected. Of course, it is unknown in how many specimens which showed remanence from the beginning, this property had been induced artificially at some previous field or laboratory examination. Of a very few specimens I am practically certain that they had not been touched with a magnet before. In the magnetite quarries on the East Mesabi Range a certain rich layer, for example, is lodestone. All the specimens that had been used in the slow oxidation experiments [12] were also tested. They showed no different behavior, though they should have been more like lodestone if Newhouse's hypothesis is correct.

These experiments show the care that is necessary in order to keep magnetite unpolarized. It would probably be sufficient to produce polarity to have specimens closely associated with good lodestone in the trays. It is, therefore, the more surprising that Newhouse, in the 59 polished sections reëxamined, found twenty-

[12] J. W. Gruner, *op. cit.*

two " to be polar and to contain brownish magnetite whereas the remaining thirty seven were non-polar and showed no brownish replacement magnetite." If the strength of polarity is " roughly proportional to the amount of oxidized magnetite present " it is rather strange that our best example of lodestone from Magnet Cove contains FeO 24.46 per cent. and Fe_2O_3 67.20 per cent.[13] or a deficiency of only 5.5 per cent. of FeO which, however, is partly made up by MgO. Other analyses in the literature are similar.

Newhouse suggests that limonite is usually associated with lodestone, which seems to indicate to him that lodestone is oxidized magnetite. Why then is lodestone not more common, for there exist enormous quantities of limonite-stained magnetite? That lodestone is relatively more common on the surface and at the extremities of a magnetite deposit is not surprising. A crowding of the magnetic lines of force of the earth's field would be expected in those places. Even in a small hand-specimen the same forces produce greater magnetism at the edges than at the center of the magnetite.

I cannot follow Mr. Newhouse when he says in one of his last paragraphs: " Since the magnetic field is usually strongest at the ends of the ore body, magnetostriction may well cause some localization of ' oxidized magnetite ' there, due to stresses set up along crystal boundaries. As is well known, stressed crystals are more easily attacked by solutions than others. There would then be a tendency for more rapid oxidation by solutions in the stressed crystals at the ends of the magnetite mass." But there would be no relief from stresses, for the magnetic field would be intensified. Since the structure of oxidized magnetite seems to be the same as that of true magnetite except for the addition of some oxygen ions, the stresses should become *still greater* and the crystal structure of oxidized magnetite *less* stable than that of hematite.

Newhouse also assumes that all oxidized magnetite or ferromagnetic ferric oxide has a higher remanence than magnetite because the natural specimen as described by Sosman and

[13] J. Francis Williams, Ann. Rept. Geol. Survey Arkansas, *2*, 1890, p. 219.

Posnjak [14] possesses it. These two investigators, however, carefully avoid calling the specimen oxidized magnetite and even express some doubt that it is oxidized *magnetite*. They also show that in artificially prepared and oxidized magnetite this unusual remanence does not exist.

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[14] *Op. cit.*, p. 338.

REVIEWS

The Iron Ore Deposits of the Union of South Africa. By PERCY A. WAGNER. So. Africa Geol. Survey, Mem. 26, Pretoria, 1928. Pp. 268, plates and figures.

It is probably safe to say that the average American geologist has a very limited knowledge of the iron ore resources of Africa. Some of us, who in our early youth read the fascinating books by Paul du Chaillu, will recall the figure illustrating two natives working the bellows for a miniature blast furnace and will remember his statements that the primitive smelting of iron ores was an ancient art in this part of the world, probably practiced for the last thousand years if not more. There now seems a likelihood that a great iron industry will develop from such humble beginnings and, as we learn from Dr. Wagner's book, there appear to exist, in the Union of South Africa alone, vast reserves of iron ore.

This memoir by Dr. Wagner is a most excellent book splendidly written and illustrated, and full of scientific data of the deepest interest. The descriptions, while detailed, are not tiresome and continually bring out the facts as to the origin of the ores by well chosen illustrations of thin sections, profiles and maps. The reviewer wishes to compliment the author for his excellent work. All of it, of course, is not his own; much information was obtained from earlier work by Hall, Du Toit and many others.

To begin with, then, we find that there is a comparatively small reserve—122,000,000 tons—of high grade ore of 50 to 60 per cent. Second, a very large reserve—5,900,000,000 tons—of medium grade ore, containing 35 to 45 per cent. Third, 2,140,000,000 tons of high grade titanic iron ore, not usable at present but certainly of potential value. Fourth, a quite fabulous amount of possible, low grade ore. Altogether the reserves are of the same order of magnitude as those of Brazil, England and France but are smaller than those of the United States of America. Naturally, not too much weight should be attached to these figures, but they are certainly impressive.

We learn further that the ores are found in the Transvaal, in the Natal, in Griqualand West, but not to any amount in the Cape Colony, nor in the Orange Free State. The relatively small amount of 60 per cent. ore

is found in the Transvaal and consists of concentration deposits from lower grade ore, not unlike our Lake Superior first class ores. The large amount of medium grade ore occurs in Central and East Transvaal, in the Pretoria series, and is referred to as "magnetic quartzite." The next large reserve of medium grade ore is contained in the Karroo formation (Permo-Triassic) where it occurs with or near the coal beds and mainly in the Prestwich field in Natal.

Ancient workings from pre-European time are found in many places. Actually there is now a blast furnace of 150 tons capacity in operation at Newcastle, Natal, and steelworks of a capacity of 30,000 tons per annum have been erected at Pretoria, with an experimental furnace. Attempts are now being made to consolidate the industry under government auspices with a bonus of 15 to 25 shillings per ton of pig iron.

Geologically speaking the ores are of many kinds: Those classified as of "igneous origin" (a designation not quite fortunate) comprise the magmatic segrations, the "contact metasomatic," and the "lode or vein deposits." Then there are the ores of sedimentary origin, including the "banded ironstones" and the Karroo ores. Finally, the secondary concentrations of the Lake Superior type and the lateritic ores, the latter of small importance in this part of subtropical Africa.

As to age, the ores are grouped as follows:

1. Bedded ores of the Karroo system.
2. Cape System (Devonian); no ores.
3. Waterberg System (age ?); bedded ores of Griqualand West.
4. Transvaal System (pre-Cambrian).
   a. Bushveld Complex.
   b. Bedded ironstones of the Pretoria and Dolomite series.
5. Ventersdorp and Witwatersrand Systems (pre-Cambrian). Banded ironstones.
6. Swaziland System (early pre-Cambrian). Banded ironstones.

The Karroo ores, which occur mainly in Natal and East Transvaal, are characteristic "blackbands" in, or below, coal beds of the flat dipping Ecca series accompanied by basic flows or intrusions. These beds, which are from 2 to 3 feet thick, now furnish 59 per cent. ore for the Newcastle furnace, P: 0.2 per cent., S: 0.2 per cent. The principal ore mineral is siderite, but magnetite appears where the beds have been metamorphosed by dolerite intrusions. The average of the ore will, of course, not reach the figure indicated. The coking coal of the Karroo is used for smelting.

Next follow the great reserves of oölitic ores of the Transvaal System in the Pretoria and Dolomite series. The description of these is very interesting. The principal bed is an extraordinary persistent bed of "arenaceous oölitic ironstone" traceable for 200 miles in the eastern part

of the Transvaal with a thickness of 5 to 20 feet. This is also known as the "magnetic quartzite." The ore runs 45 to 48 per cent. Fe, 0.1 to 0.29 P, variable sulphur, up to 0.56 per cent. but generally low. Several smaller bands occur in the quartzite above the ore. There are alternating layers of quartz-rich and quartz-poor material. The texture is typically oölitic, the small oölites often having a kernel of quartz, which may be partially replaced by octahedral magnetite. The ore is composed of detrital quartz grains and small concentric oölites, the latter consisting of alternating layers of magnetite, chamosite, the interspaces being filled by chamosite, hematite and calcite.

The mineralogical composition is 35 per cent. magnetite, 28 per cent. chamosite, 17 per cent. hematite, 1.26 per cent. calcite. Vanadium is present, also traces of molybdenum and chromium; this seems to indicate that these metals are here of biochemical origin. Other horizons within the contact aureole of the Bushveld laccolith show andalusite, specularite, magnetite, and muscovite, the latter accompanied by roscoelite (this is a new type of occurrence of the vanadium mica). The magnetite in the normal ore can not, however, be attributed to contact metamorphism, for it alternates with chamosite. The normal deposits are primary sediments of deltaic or estuarine origin, and can in no way be interpreted as a replacement of calcite. In their present form they seem to constitute a new type of ore.

At Postmasburg, in Griqualand West, the manganese deposits in the flat lying Matsop series, above the Transvaal series, are accompanied by some bedded iron ores.

The "banded ironstones" of the Witwatersrand and Swaziland systems form another subject of absorbing interest. These ores are generally of low grade but have a widespread occurrence and are evidently entirely analogous to the "banded jaspers" of the Lake Superior region. They are older than the oölites of the Transvaal system. The problem increases in interest when we recall the widespread occurrence of similar old rocks in Rhodesia and other parts of Central Africa, as well as in Western Australia. They clearly represent sedimentary iron ores deposited under conditions differing from those under which oölites and other more modern types of iron ores were formed. A detailed description of the banded ironstones is given from which it appears that they form beds ranging in thickness from a few feet to 800 feet, with a composition of approximately 40 per cent. SiO_2, 56 per cent. Fe_2O_3 and 3.22 per cent. FeO. They are considered as probably sideritic cherts, of shallow water origin, but now show rapidly alternating layers of silica (ranging from red to gray cryptocrystalline jasper to saccharoidal quartzite) and layers of fine-grained red hematite, with a little magnetite. The hematite contained in the chert often shows pseudomorphic forms

after siderite. Du Toit has shown that, by weathering, the magnetite of these rocks is partly converted into hematite. The beds are contained in quartzite and shale. By contact metamorphism these ores pass into lustrous quartz-hematite schists, or into schists with amphibole, sillimannite and garnet. In places, but apparently not as a result of contact metamorphism, the iron has passed into crocidolite, or of amosite asbestos in layers parallel to the bedding.

The present mineral hematite is supposed to have been derived from siderite by oxidation but the reason for this oxidation is not explained in detail. High grade ores result locally from solution of the quartz (as in the Lake Superior region) but an additional explanation given is that part of the quartz has been replaced by hematite. Such deposits occur at Crocodile River, Rustenburg, Transvaal, and carry Fe, 66 per cent., P, .006 per cent. to 0.05 per cent.

In the Witwatersrand system there are three horizons of these banded ironstones: the Hospital Hill, Government Reef and Water Tower slate, each several hundred feet thick.

If space were not running short, I would like to bring out the many extremely interesting points about the titanic iron ores of the Bushveld Complex. As well known this complex forms an enormous laccolithic (lopolithic) intrusion in the flat dipping Pretoria beds of the Transvaal system. It is at least 25 miles wide and its composition ranges from diabase at the base, through a great thickness of norite, to granite. This is in the central part of Transvaal. The ores form flat sheets, often wonderfully persistent, dipping in the intrusive. In the lower norite are first two sheets of chromite (Cr_2O_3, 28 to 50 per cent.), now mined, the ore averaging 42 per cent. In 1926, 3,000 tons were shipped. The ore is high in FeO, this being penalized. The composition is about 68 per cent. chromite, 27 per cent. picotite, 1 per cent. magnetite, with some MgFe silicates.

Above the chromite follows the Merensky platinum horizon. Far above this and not far below the top of the norite is the horizon of titanic iron ore, continuous for miles with a thickness averaging 4 feet, often lenticular and replaced by other lenses along the same horizon. It is associated with layers, or lenses, of anorthosite.

The flat outcrops are bent over at the surface, and attempts are made to calculate the amount of degradation since Cretaceous time by the dropping of the outcrops. It is estimated at 80 feet. At Magnet Heights are five distinct horizons, the lower 6 to 10 feet thick. Tonnage is calculated to 24,000,000. The layers are quite sharply defined, above and below. The oxidation near the surface has produced Fe_2O_3, which is magnetic. All the surface material is of this kind, which the author calls "Maghemite," and this is mixed with more or less ilmenite. It

carries about 55 per cent. Fe, 14 to 20 per cent. TiO_2, and up to 1 per cent. vanadium.

As to origin, the titanic iron is always later than the silicates. Sometimes, indeed, as at Tugela, Natal, there are dike-like masses in the norite. It is assumed that the underlying norite was already consolidated when the upper layer of iron ore was segregated. Presence of some biotite indicates coöperation of volatile constituents. The total length of the outcrop of the titanic iron ore is estimated to 200 miles, with an average thickness of 4 feet.

In the felsites, agglomerates and tuffs belonging to the Rooiberg series are layers and patches of hematite which are classed as contact metasomatic deposits and belong to the metallization of the roof of the Bushveld Igneous Complex.

It has proved a difficult task to abstract adequately and briefly the wealth of material in Dr. Wagner's book, but I feel sure that many of the deposits which he has described will be of absorbing interest to those who have studied the iron ores of our own country.

W. LINDGREN.

Ore Deposits of Magmatic Origin, their Genesis and Natural Classification. By P. NIGGLI. Translated by H. C. Boydell. Revised and supplemented by Dr. Niggli and Dr. R. L. Parker. Pp. viii + 93, figs. 12. Thomas Murby & Co., London, 1929. D. Van Nostrand Co., New York. Price, $3.50.

The widely quoted treatise of Dr. Niggli on magmatic ore deposits has been translated and revised so that in its new form it represents the most modern attempt to develop a systematic classification of the phenomena relating to magmatic ore deposition constructed on a physico-chemical and tectonic basis. As is well known by those familiar with Dr. Niggli's work, his thesis is that "ore deposition is a part problem of magmatic differentiation in its widest sense." The volume which has been translated is a demonstration that this thesis is a reasonable one and that the problems encountered in the study of magmatic ore deposits are parts of the wider problem relating to the origin of igneous rock. The translation is well done and concise. It follows the German very closely, but the style is smooth and clear. The book is well worth reading by all petrographers and students of ore deposits. W. S. BAYLEY.

Function of Natural Gas in the Production of Oil. By H. C. MILLER. Pp. 256, figs. 36, tables 24. American Petroleum Institute, New York, 1929. Price, $2.00.

This volume is a report of the U. S. Bureau of Mines in coöperation with the Division of Development and Production Engineering of the

American Petroleum Institute based on data gathered and reported by the Kansas and Oklahoma, Pacific Coast, Rocky Mountain, and Texas and Louisiana regional committees of the Gas Conservation Committee of the American Petroleum Institute. It is thus an authoritative compilation of the results of the experience of many individuals working in many fields, gathering into one volume the most significant of the great mass of data that has appeared in the oil journals on the gas lift and repressuring. Since the author is Senior Petroleum Engineer of the Bureau of Mines, the vast amount of information possessed by that body was available in the writing of this book.

To the geologist the principles underlying the gas lift and repressuring are of considerable interest. It may be stated briefly that the aim of the petroleum engineer in employing these methods of securing greater production is to restore the oil to the state in which it was before the wells from which it is being produced were drilled and to maintain as much as possible the original relation between oil and water. It is therefore necessary to obtain as much information as possible regarding the original state of the oil, the effect of dissolved gas on surface tension and viscosity, the effect of surface tension and viscosity on the movement of oil through sand, and similar problems. Most of the book deals with these problems from a purely scientific standpoint rather than from an engineering standpoint.

The book is divided into two parts, of which the first deals with the importance of natural gas in the recovery of oil, and discusses the methods of controlling gas and oil production to gain the greatest ultimate recovery. The second part deals with the importance of natural gas in the conservation and production of petroleum, and takes up many of the physico-chemical effects of gas upon oil. In this section, there is a discussion of the "importance and effect of adsorption; the solubility of gases in petroleum; the Jamin action as effecting the movement of oil and gas through reservoir sands; and the effect of natural gas, occluded or dissolved, upon the viscosity, surface tension, adhesion and extractibility of petroleum."

In order to understand the geology of petroleum, the reviewer feels that it is essential that a book of this kind should supplement the usual texts on petroleum geology. Coöperation between the geological and production departments of oil companies is increasing daily and this book is of great value in helping to bridge the gap between these two groups.

W. V. HOWARD.

UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS.

Assimilation and Petrogenesis; Separation of ores from magmas. By JOHN STANSFIELD. Pp. 197, pls. 30, figs. 60. Valley Publishing Co., Urbana, Illinois.

This is essentially a record of experiments carried out at the University of Illinois, and undertaken to study the mode of crystallization of igneous rocks and to throw light on the question of assimilation in rock melts. In an introduction of 50 pages the various theories for the dissimilarity of igneous rocks are explained; these include original heterogeneity of the materials, later magmatic differentiation and lastly assimilation, effected by the melting of foreign rocks submerged in the magma. The field evidence of assimilation is discussed in considerable detail, the assimilated rocks being siliceous or argillaceous sediments, limestones or igneous rocks. Regarding the importance of this assimilation or syntexis (to use a term coined by Professor Daly) opinions differ rather widely. All authors agree, however, that it may take place, although many deny that it is a factor of great importance. Others see no difficulty in dissolving large masses of solid rocks in a magma. Evidently it is a problem of the amount of heat available. In general, the conclusion of the author is, that assimilation is a process which must be reckoned with, although perhaps 10 or 15 per cent. may represent the amount of foreign material which can be assimilated by a magma. The subject of inclusions and mixed or "hybrid" rocks is discussed in detail in Chapter II. A large number of experiments were planned in which a chosen series of ten igneous rocks ranging from granite to peridotite would be caused to assimilate sedimentary materials: (1) calcite; (2) pure kaolin; and (3) pure glass sand. The material was ground to 100 and 150 mesh and intimately mixed, the proportions being different. Temperatures of from 1,000° to 1,600° were reached in electric furnace, or 1,230° to 1,410° in a brick furnace, and the high heat maintained for two hours. The cooling took from two hours to seven days, the latter in the brick kilns. This, of course, is assimilation under particularly favorable conditions, quite different from those where large masses of the foreign material is immersed in the magma.

Assimilation of calcite yielded melilite or åkermanite (positive, medium birefringence). The assimilation of kaolin yielded in part glassy products. Kaolin with kimberlite yielded cordierite; in some melts feldspars resulted. Assimilation of quartz was only partial, which would throw doubt on the syntexis of large masses of siliceous sediments in magmas. Assimilation of dolomite is complete, yielding products like those of the peridotite-limburgite series; siderite or tremolite schist likewise yielded similar products. The assimilation of bauxite is incomplete, in some cases yielding sillimanite-andalusite products. This rather argues against the syntexis of large amounts of argillaceous sediments. Many experi-

ments were also made with admixture of magnetite and hematite; the assimilation was partial or complete with glass in varying proportions. Various rocks and magnetite yielded peridotic magmas. New minerals (not in the parent rocks) formed in the experiments were as follows: åkermanite, melilite, monticellite, riebeckite and perowskite formed by assimilation of calcite; cordierite, plagioclase, sillimanite, and spinel, by the assimilation of kaolin; plagioclase, spinel and sillimanite, by the assimilation of bauxite; augite, olivine and garnet, by the assimilation of magnesite; augite, and olivine, by the assimilation of tremolite; bronzite, enstatite, and olivine, by the assimilation of iron-bearing materials; enstatite and clino-enstatite, by the assimilation of quartz.

A considerable number of melts of rocks with sulphides were made, such as chalcocite, bornite, chalcopyrite, pyrite and pyrrhotite. Naturally the gas phase and the pressure and the graphite of the crucible come into play here and thus the results lack some of the definiteness which would have been attained under pressure and in a neutral atmosphere. The sulphides were generally found to be divided in minute drops, and the very important observation was made that particles tend to float, buoyed up by minute gas bubbles (see photographs) thus demonstrating the principle of flotation in magmas. Chalcocite was in part reduced to native copper; bornite and chalcopyrite, in part to chalcocite; pyrite turned to pyrrhotite, while the latter was little altered. In some basic melts all the sulphide had disappeared. Sphalerite recrystallized in dendritic form in some melts.

The experiments—some 500 in all—are described in detail and the products illustrated by photographs of thin sections.

Part 2 of the book deals with the separation of ores from magmas, particularly the marginal concentration. Instead of forming new minerals uniformly distributed, the sulphides tended to accumulate in globules along the base, or sides, or the upper part of the ingot. Therefore, for ore segregation in a magma, gravity is certainly not the only determining factor in dry melts. The theory of separation of sulphides from magmas is discussed in some detail.

Altogether, this book is a record of extensive and painstaking work, and the experiments which the author has carried out throw much light on the two processes which he sought to elucidate, *i.e.*, assimilation of foreign products, and the separation of ores in magmas. It is a contribution of much value to the difficult subject of petrogenesis.

W. LINDGREN.

Ball Clays. Special Reports on the Mineral Resources of Great Britain. Vol. XXXI. By ALEX SCOTT. Pp. iii + 73, figs. 7. Geol. Survey, London, 1929. Price, 2s. 6d.

This report on the ball clays in the southwest of England deals with "the mode of occurrence, the origin, the geological relations and the mineralogical character of "those plastic, transported clays which, when fired in an oxidizing atmosphere to the temperature of . . . approximately 1150°–1200° C., have a white or nearly white color." There are only three deposits in Great Britain, near Wareham in Dorset, near Newton Abbot in S. Devon, and near Petrockstow in N. Devon. They are generally associated with lignite and all are of Tertiary age. Each of the deposits is discussed in detail and the utilization of their products in local clay works is described.

Chemical and thermal study of the clays indicates the presence in them of a large quantity of kaolin, some colloidal material, quartz, and the usual residual components of clays. The book concludes with a description of the physical properties of ball clays and of the methods of testing them.

W. S. BAYLEY.

A Cartographic Correction for the Eötvös Torsion Balance. By C. A. HEILAND. 17 pp. A. I. M. E. Tech. Pub. No. 52, 1928. Also in A. I. M. E. "Geophysical Prospecting, 1929," pp. 544–560.

The "cartographic correction" is the correction for the effect of the topography beyond 100 meters from the instrument. Eötvös used a simple but approximate formula—Schweydar used more rigorous formulae. The writer divides the terrane into zones bounded by radii and concentric circles. By assumption of certain approximations, a formula is derived which depends on certain coefficients and the square of the elevation referred to the center of gravity of the instrument as the origin. Rule of thumb tabular calculation forms, including the coefficients, can be set up; the squares of the elevations are entered in the proper spaces and added or substracted and multiplied by an indicated routine. The respective calculations for U_{xx}, U_{yz}, U_{xy}, and U_{Δ} each require a separate form.

This is a valid method of calculating the cartographic correction. But this type of method of calculation of the correction is being superseded by graphical methods or methods making use of tables of effects rather than tables of squares.

D. C. BARTON.

BOOKS RECEIVED.

The Country around Oswestry. By C. B. WEDD, S. SMITH, W. B. R. KING AND D. A. WRAY. Memoirs Geol. Survey of England and Wales. London, 1929. Price 5s. 6d.

A detailed account of the much folded area in Shropshire, England, and Denbigh and Montgomery, Wales, containing abandoned coal beds in the Middle and Upper coal measures, old lead (galena) mines in Ordovician and Carboniferous limestones, zinc (sphalerite) deposits in Ordovician beds, and copper and cobalt ores in Paleozoic and Triassic rocks.

Annual Report of the Director (Relatorio Annual do Director), Geol. and Miner. Survey of Brazil, 1927. E. P. DE OLIVIERA, Director. Pp. 170, index. Rio de Janeiro, 1929. (In Spanish.)

Contains tables of imports of iron, coal, etc., in 1926 and 1927. Catalogue of Minerals, with Analyses (Catalogo da Collecção de Mineraes, com as Analyses dos principaes Minerios.) Exposicao Internacional de Sevilha, 1929. Pp. 30, analyses 194. Rio de Janeiro, 1929.

The Mineral Industry during 1928. Edited by G. A. ROUSH. Vol. 37, 1928, pp. 802. McGraw-Hill Book Co., New York. Price, $12.00.

Geology and Water Resources of the Edgeley and La Moure Quadrangles, North Dakota. By H. A. HARD. Pp. 90, pl. 5, figs. 7. U. S. Geol. Survey Bull. 801, 1929 (Sept.).

General geology; geologic history; building materials; soils; artesian water.

U. S. Geol. Survey Water Supply Paper 597, Part C: Problems of Soft Water Supply of the Dakota Sandstone, with special reference to conditions at Canton, South Dakota. By O. E. MEINZER. Pp. 147–170; pl. 1, figs. 4. **Part D: Geology and Water Resources of the Upper McKenzie Valley, Oregon.** By H. T. STEARNS. Pp. 171–188; pl. 3, figs. 2. 1929 (Sept.).

A Study of the Crude Oil Produced in the Salt Creek Field, Wyoming. By H. P. RUE AND I. N. BEALL. Pp. 25, figs. 5. U. S. Bur. of Mines, Tech. Paper 449, 1929 (Sept.).

Bibliography of Petroleum and Allied Substances, 1922 and 1923. By H. BRITTON. Pp. 667. U. S. Bur. of Mines Bull. 290, 1929 (Aug.). Price, $1.00.

Petroleum Refining Statistics, 1927. By G. R. HOPKINS. Pp. 93, figs. 4. U. S. Bur. of Mines Bull. 297, 1929 (Aug.).

Strontium from a Domestic Standpoint. By R. M. SANTMYERS. Pp. 19. U. S. Bur. of Mines, Econ. Paper 4, 1929 (Aug.).

Coal in 1927. By F. G. TRYON, O. S. KIESSLING, and L. MANN. U. S. Bureau of Mines, Min. Res. 1927, Part II, pp. 327–509, tables, figs. 17. 1929 (May). Price, 30 cts.

Geology of Ste. Genevieve County, Missouri. By S. WELLER and S. ST. CLAIR. Pp. 352, pl. 15, figs. 5, top. and geol. maps. Missouri Bur. Geol. and Mines, vol. 22, 2d ser. Rolla, 1928 (Sept., 1929).

Excellent treatise of stratigraphic, structural and historical geology; waters, quarries, copper, and lead.

Missouri Bureau of Geology and Mines, Biennial Report of the State Geologist. Pp. 112, pl. 6. Rolla, 1929 (Sept.).

Abstracts of Scientific and Technical Publications from the Mass. Inst. of Technology, No. 4. Pp. 75. Cambridge, July, 1929.

Geology of Hyder and Vicinity, Southeastern Alaska; with a reconnaissance of Chickamin River. By A. F. BUDDINGTON. Pp. 124, pl. 14, fig. 1. U. S. Geol. Surv. Bull. 807, 1929 (Sept.).

Good discussion of geology and of silver, gold, and lead deposits; detailed description of mines and prospects.

Quality of Water of the Colorado River in 1926–1928. By C. S. HOWARD. Pp. 13, figs. 3. U. S. Geol. Surv. Water Supply Paper 636–A, 1929 (Aug.).

The Sudbury Nickel Intrusive: Contributions to Canadian Mineralogy, 1929. By A. P. COLEMAN, E. S. MOORE, and T. L. WALKER. Pp. 54, figs. 5, pl. 3. Univ. of Toronto Geol. Series No. 28.

Microscopic and chemical study of the nickel intrusive; 51 new analyses along 4 sections indicate gradation from basic to acid phase; brief discussion of genesis.

Specific Heats of Gases at High Temperatures. By E. D. EASTMAN. Pp. 27, figs. 11. U. S. Bureau of Mines, Tech. Paper 445, 1929.

Critical review of investigations and calculations.

Factors Governing the Entry of Solutions into Ores during Leaching. By J. D. SULLIVAN, W. E. KECK, and G. L. OLDBRIGHT. Pp. 38, figs. 15. U. S. Bureau of Mines, Tech. Paper 441, 1929 (Sept.).

Interesting study of theory and practice of penetration of copper sulphate solutions into copper ores of the Southwest.

Precipitation of Lead and Copper from Solution on Sponge Iron. By G. L. OLDBRIGHT, H. E. KEYES, V. MILLER and W. A. SLOAN. Pp. 131, figs. 43. U. S. Bureau of Mines, Bull. 281, 1928 (July, 1929). Price, 35 cents.

Exhaustive, detailed, experimental studies.

Iron Oxide Reduction Equilibria: a critique from the standpoint of the phase rule and thermodynamics. By O. C. RALSTON. Pp. 326, figs. 112. U. S. Bureau of Mines, Bull. 296, 1929 (Sept.).

An exhaustive treatise of the physical and chemical properties and behavior of the oxides of iron; the systems iron, iron-carbon, iron-carbon-oxygen, and iron-oxygen. Excellent.

Ground Water in Yellowstone and Treasure Counties, Montana. By G. M. HALL and C. S. HOWARD. Pp. 118, figs. 5, pl. 7. U. S. Geol. Survey Water Supply Paper 599, 1929 (Sept.).

Geology and Ground Water Resources of Central and Southern Rosebud County, Montana. By B. C. RENICK, with chemical analyses of the waters by H. B. RIFFENBURG. Pp. 140, figs. 15, pl. 12. U. S. Geol. Survey Water Supply Paper 600, 1929 (Oct.).

Considerable stratigraphy and structure.

Geologic Map of Arkansas: scale 1 to 500,000. Prepared by Arkansas Geol. Survey; edited by H. D. MISER and G. W. STOSE; engraved and printed by U. S. Geol. Survey. Published by Arkansas Geological Survey, Little Rock, 1929 (Oct.). Price, $1.50; postage and container, 30 cts; total, $1.80.

Another excellent geological map of a whole state, containing much economic data regarding power lines, oil and gas pipe lines, mines, quarries, oil and gas fields.

Moraines and Shore Lines of the Lake Superior Basin. By FRANK LEVERETT. Pp. 72, figs. 10, pl. 8. U. S. Geol. Surv. Prof. Paper 154–A, 1929 (Oct.).

Drainage; glacial features; pre- and post-glacial lakes.

Upper Cretaceous Formations of Southwestern Arkansas. By C. H. DANE. Pp. 215, figs. 4, pl. 29, geol. map. Arkansas Geol. Survey Bull. 1. Little Rock, 1929 (Sept.). Price, paper, $1.70; cloth, $1.95.

Detailed discussion of Cretaceous and Tertiary systems; structure; physiography; correlation of deep wells.

SCIENTIFIC NOTES AND NEWS

V. M. Goldschmidt, professor at the Mineralogical Institute at Oslo, is now at Goettingen, Germany, Grüner Weg No. 8.

Waldemar Lindgren has gone on a five weeks' trip to Europe, and expects to return by the end of November.

Charles R. Fettke, professor of geology at the Carnegie Institute of Technology, Pittsburgh, W. A. Copeland, assistant professor, and W. H. Siefert, completed the geological survey of the Bradford oil field during the summer for the Pennsylvania State Survey.

B. S. Butler, of the U. S. Geological Survey, has returned to the University of Arizona after a summer of field work in Colorado.

W. J. Wright, who has spent several years in specializing in oil geology, began work on October 1st as mineralogist for the Province of New Brunswick.

W. C. Mendenhall, chief geologist of the U. S. Geological Survey, recently had a conference with J. A. Fulton, director of the Mackay School of Mines, Nevada, with reference to coöperative geological work in that State.

Frederick J. Clapp, of New York City, has been spending the past year in work in Europe, and has opened an office in Paris, specializing on oil and gas development in the East. His address is 28 Rue de Poussin, Paris XVI, and his cable address is "Consultoil Paris."

Reno H. Sales, chief geologist of the Anaconda Mining Co., Butte, Montana, recently spent some time in New York City.

Scott Turner, director of the U. S. Bureau of Mines, is attending the World Engineering Congress at Tokio.

R. J. Colony, of Columbia University, spent September doing geological work for the Saratoga Commission in New York State.

George H. Garrey lately examined the area near the Pittsburgh, Amethyst, and Del Monte claims at Creede, Colo., in the interests of the Sloan-Amethyst Leasing Company, the P. and E. Leasing Company, and the Reynolds-Morse Corporation. He is now in Gunnison County, Colorado, doing geological mapping in the Lime Bluff Mining district.

C. K. Leith, of the University of Wisconsin, is attending the World Engineering Congress at Tokio.

G. H. Ashley, state geologist of Pennsylvania, spent last summer in

collecting material for his forthcoming report on the "Rocks of Pennsylvania."

E. L. Bruce, after a season in northern Manitoba and Saskatchewan in the interests of Ventures, Ltd., has returned to Queen's University, where he occupies the Miller Memorial Chair in Geology.

A. C. Veatch, of New York City, is on a trip to Africa.

Sir Stopford Brunton is at Queen's University, Kingston, Ontario, this fall, as a research fellow in Geology.

George W. Roddewig, formerly associated with the W. A. Clark interests in Montana, is now in Salt Lake City, Utah, where he has an office for mining engineering and geological work.

B. L. Miller, of Lehigh University, assisted by L. W. Fisher, has been making a study of the limestones of Pennsylvania, and will publish a report on the subject.

R. W. Stone, assistant state geologist of Pennsylvania, is making a study of the building stones of the State.

Quentin D. Singewald has accepted a position as assistant professor of geology at the University of Rochester, and will have charge of work in economic geology.

Percy Hopkins has been appointed consulting mining engineer for Gem Lake Mines, Ltd., in Central Manitoba, Canada.

R. H. Stewart will soon sail for Sydney, Australia, to examine sand beach leases in that region, where gold, platinum, cassiterite, rutile and zircon are said to be found.

E. T. Stannard, vice-president of the Kennecott Copper Corporation, has moved to New York.

A. A. Mackay, of Montreal, was a recent visitor to New York and New Haven.

E. H. Davidson, of the Cambourne School of Mines, has returned home after a lengthy visit to Nova Scotia.

F. E. Keep has resigned from the Southern Rhodesia Geological Survey to join the staff of the City Deep mine at Johannesburg.

Harold A. Titcomb has left London for several weeks of investigation in Serbia.

J. T. Singewald, Jr., of Johns Hopkins University, is returning in November from South and Central Africa.

W. E. Wrather is expected to return from the East Coast of Africa in November.

R. J. Parker, manager of the Rhodesian Selection Trust, has returned to the Company's properties in Northern Rhodesia after a trip to London.

A. K. Lobeck, who has been in the geology department at the University of Wisconsin, is now professor of geology at Columbia University.

James M. Hill, engineer in charge of mineral resources and statistics for the U. S. Bureau of Mines, at San Francisco, has been elected president of the California Mining Association.

Freeman Ward, of Lafayette College, has been studying the sand and gravel deposits of the Reading and Altoona districts of Pennsylvania during the field season.

Miss Julia L. V. McCord, librarian of the U. S. Geological Survey for more than 21 years, has retired and is succeeded by Guy E. Mitchell.

M. E. Hurst, formerly at Brown University, has been appointed assistant geologist in the Ontario Department of Mines, Toronto.

H. H. Hughes, of the Pennsylvania Geological Survey, has completed detailed geological mapping of the Freeport quadrangle.

E. Leitz, Inc., has opened new offices at 122 South Michigan Avenue, Chicago, Ill., and at 927 Investment Building, Washington, D. C., with complete lines of Leitz products.

The U. S. Geological Survey estimates the production of manganese at Phillipsburg, Montana, at 658,600 tons, with reserves of 1,780,000 tons.

A new edition of the large map of Washington, D. C., and vicinity, on a scale of two miles to the inch, has been published by the U. S. Geological Survey.

A map of the Big Sand Draw gas field in Wyoming was recently made available by the U. S. Geological Survey.

Hanna and Carbon Basins, Wyoming, contain 4½ billion tons of minable coal according to estimates of the U. S. Geological Survey.

A map of the Book Cliff and Wasatch Plateau coal fields in Carbon and Emery counties, Utah, has been issued by the U. S. Geological Survey.